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(54) **INSTANT EYE GAZE CALIBRATION SYSTEMS AND METHODS**

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USPC **351/206**

See application file for complete search history.

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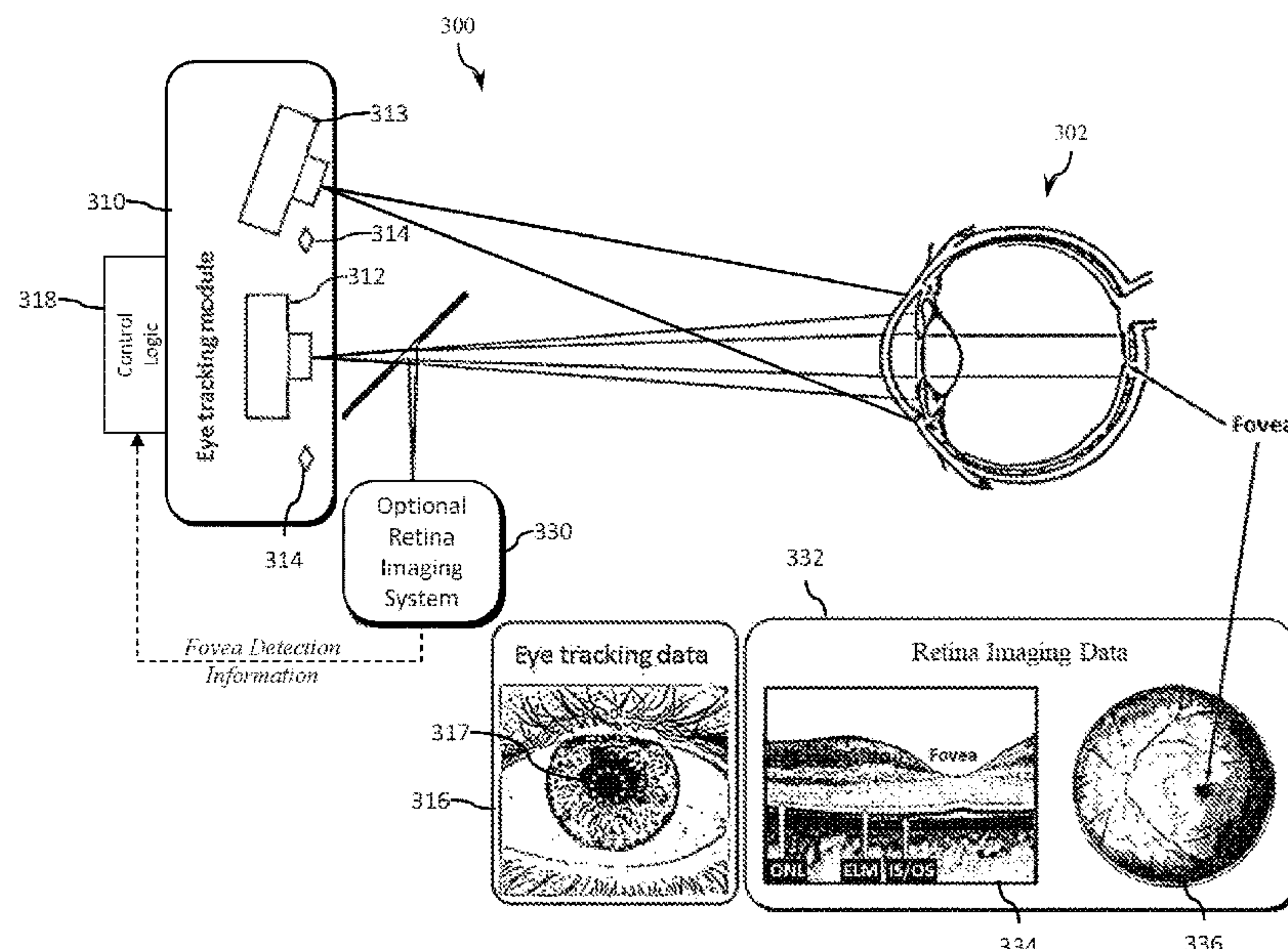
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Primary Examiner — Mohammed A Hasan

(57) **ABSTRACT**

Systems and methods for initializing and calibrating an eye tracking system include an eye tracker configured to capture a first image of an eye from a first location and a second image of the eye from a second location, and a control processor configured to detect a first plurality of eye characteristics from the first image, the eye characteristics having first corresponding image coordinates, detect a second plurality of eye characteristics from the second image, the eye characteristics having second corresponding image coordinates, and determine a calibration offset and a calibration gain. The control processor may be further configured to determine an eye fixation position and orientation relative to an optical axis of the eye tracker based at least in part on the first corresponding image coordinates and/or the second corresponding image coordinates.

18 Claims, 10 Drawing Sheets



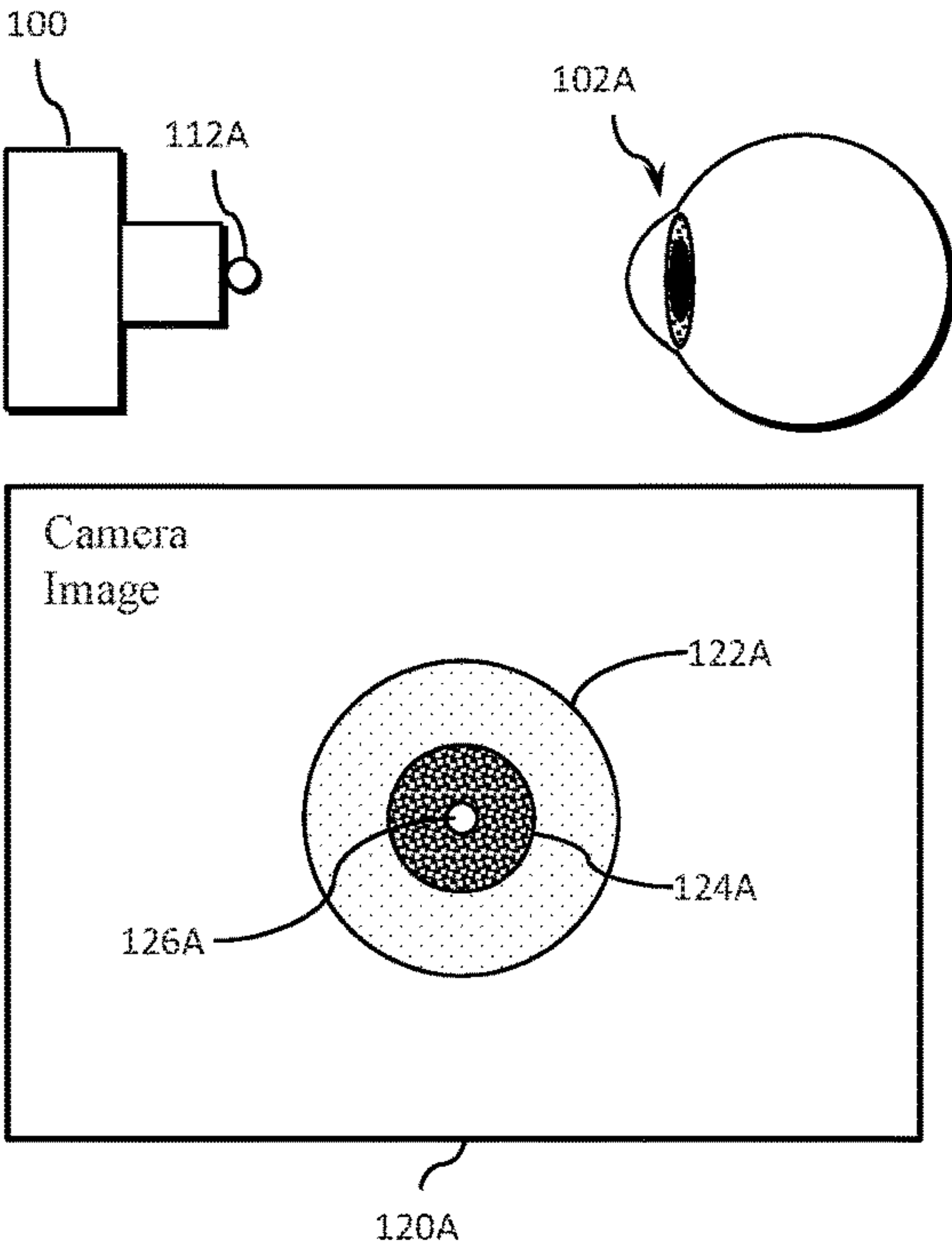


FIG. 1A

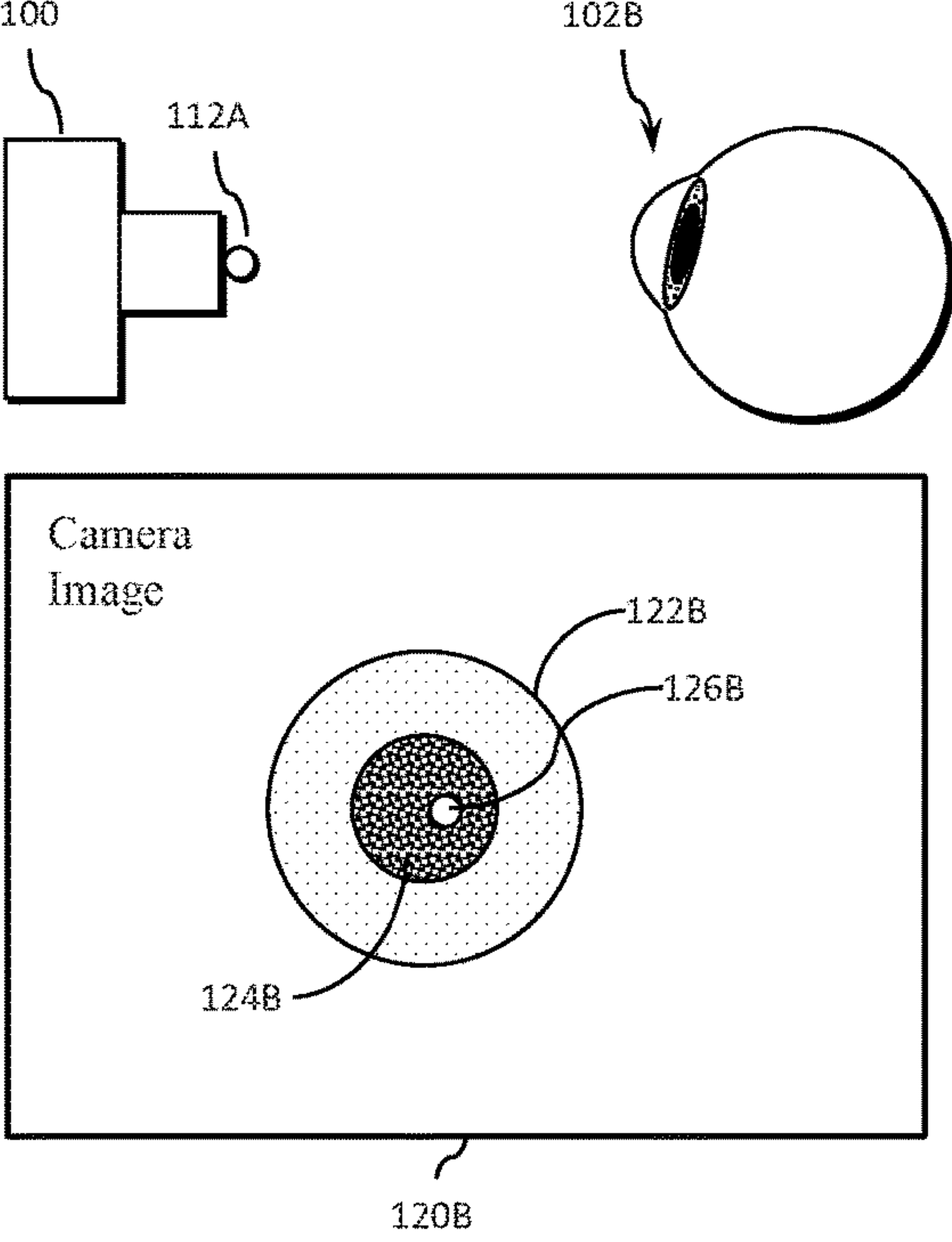


FIG. 1B

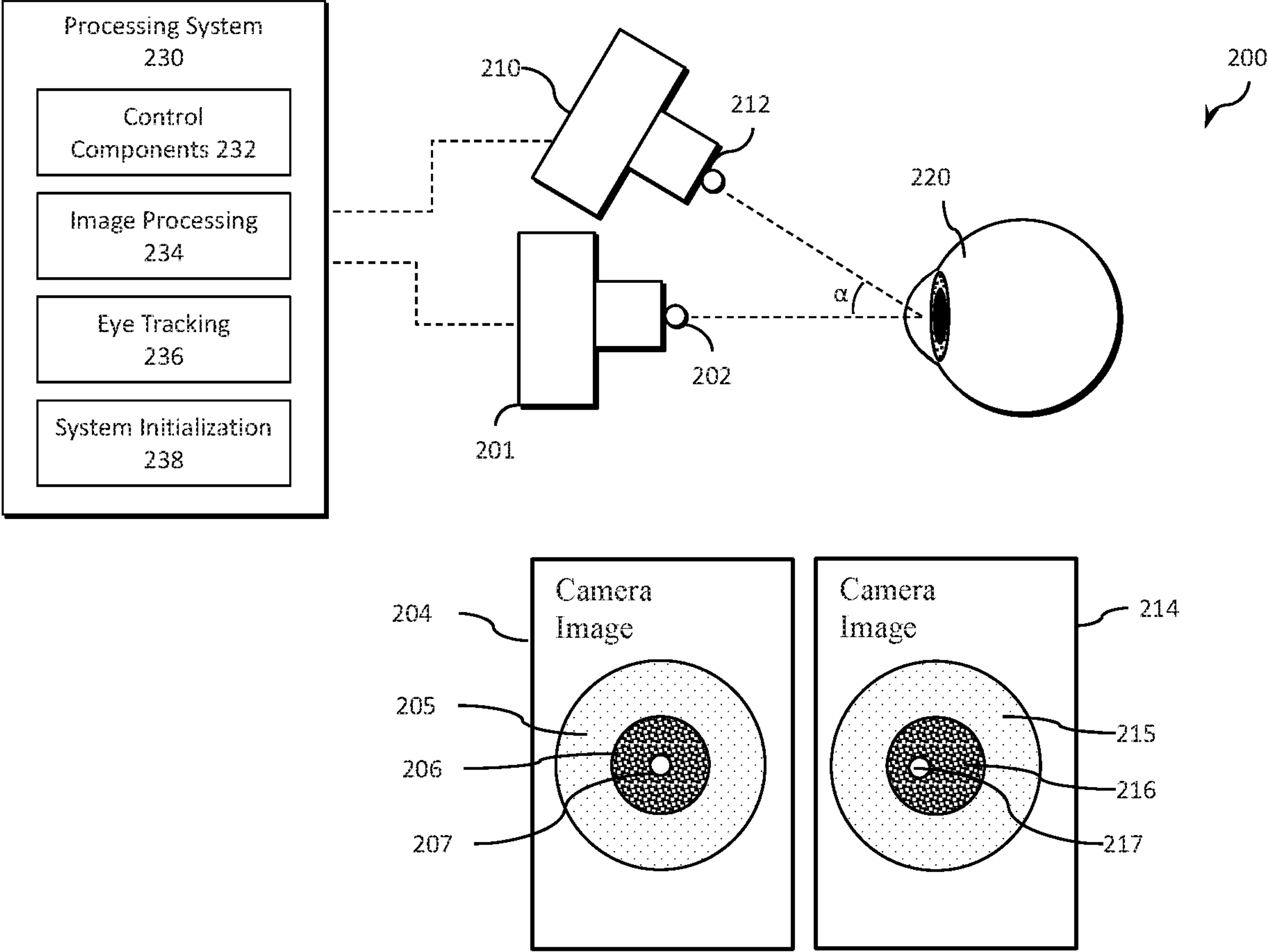


FIG. 2

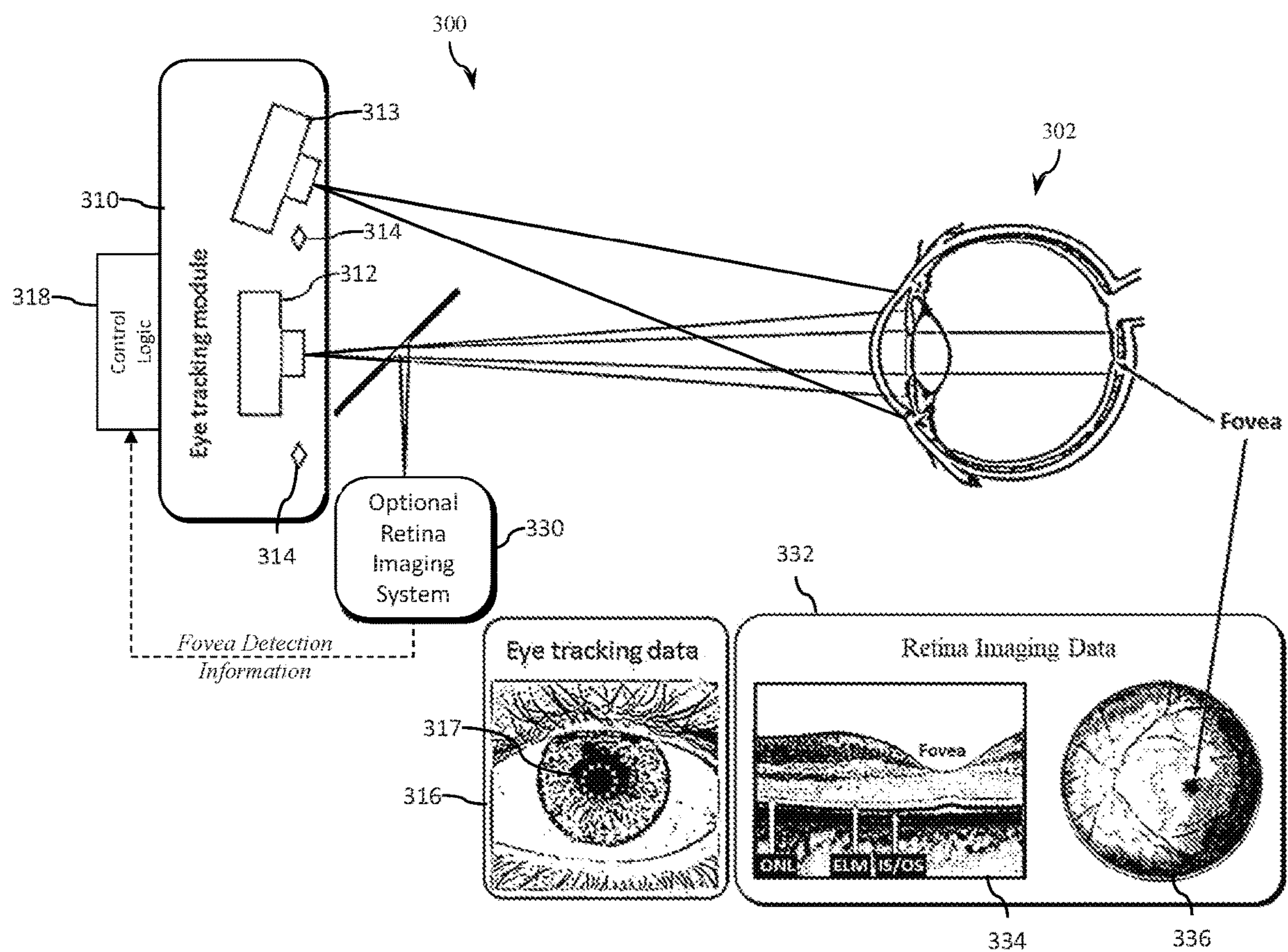


FIG. 3

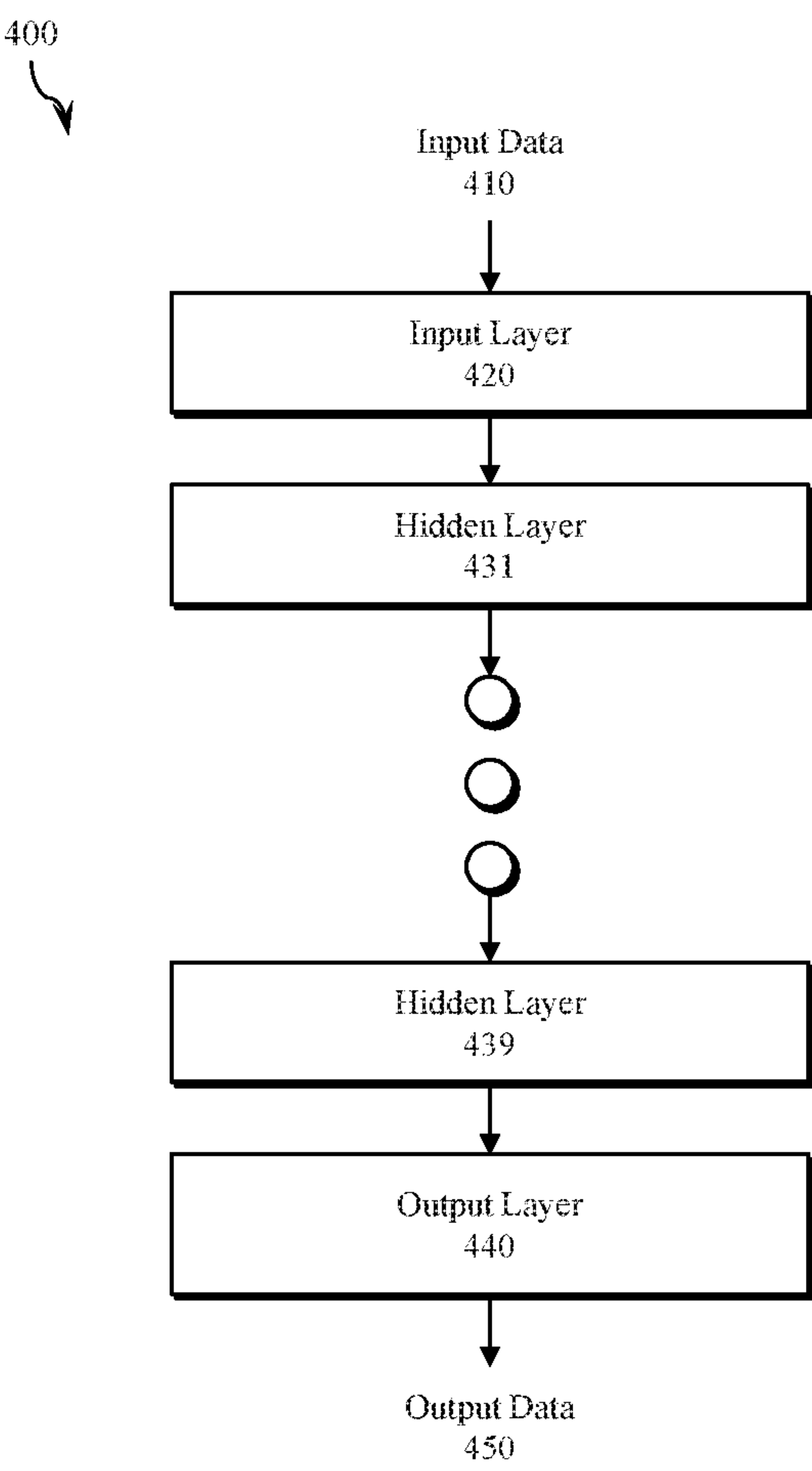


FIG. 4

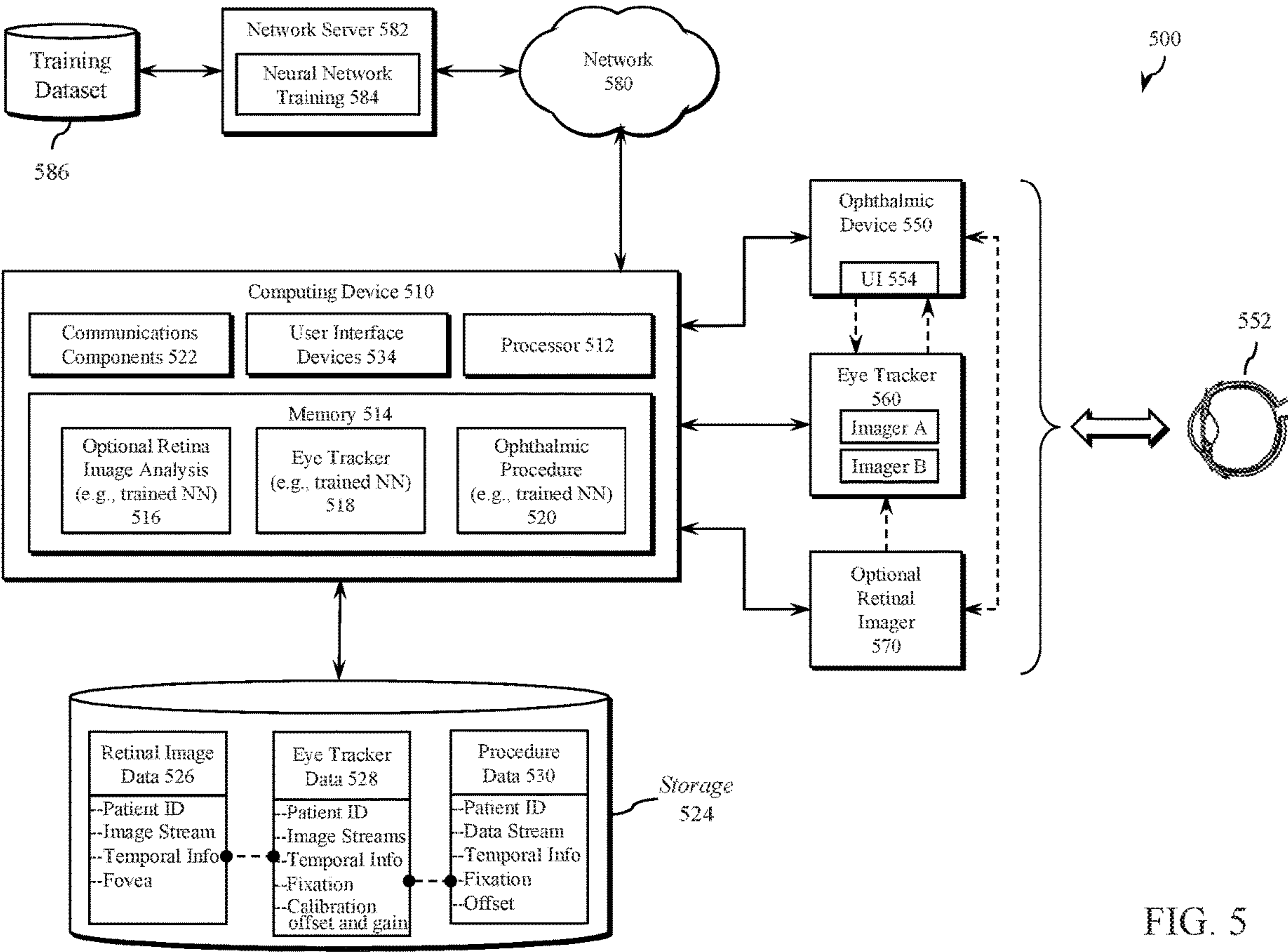


FIG. 5

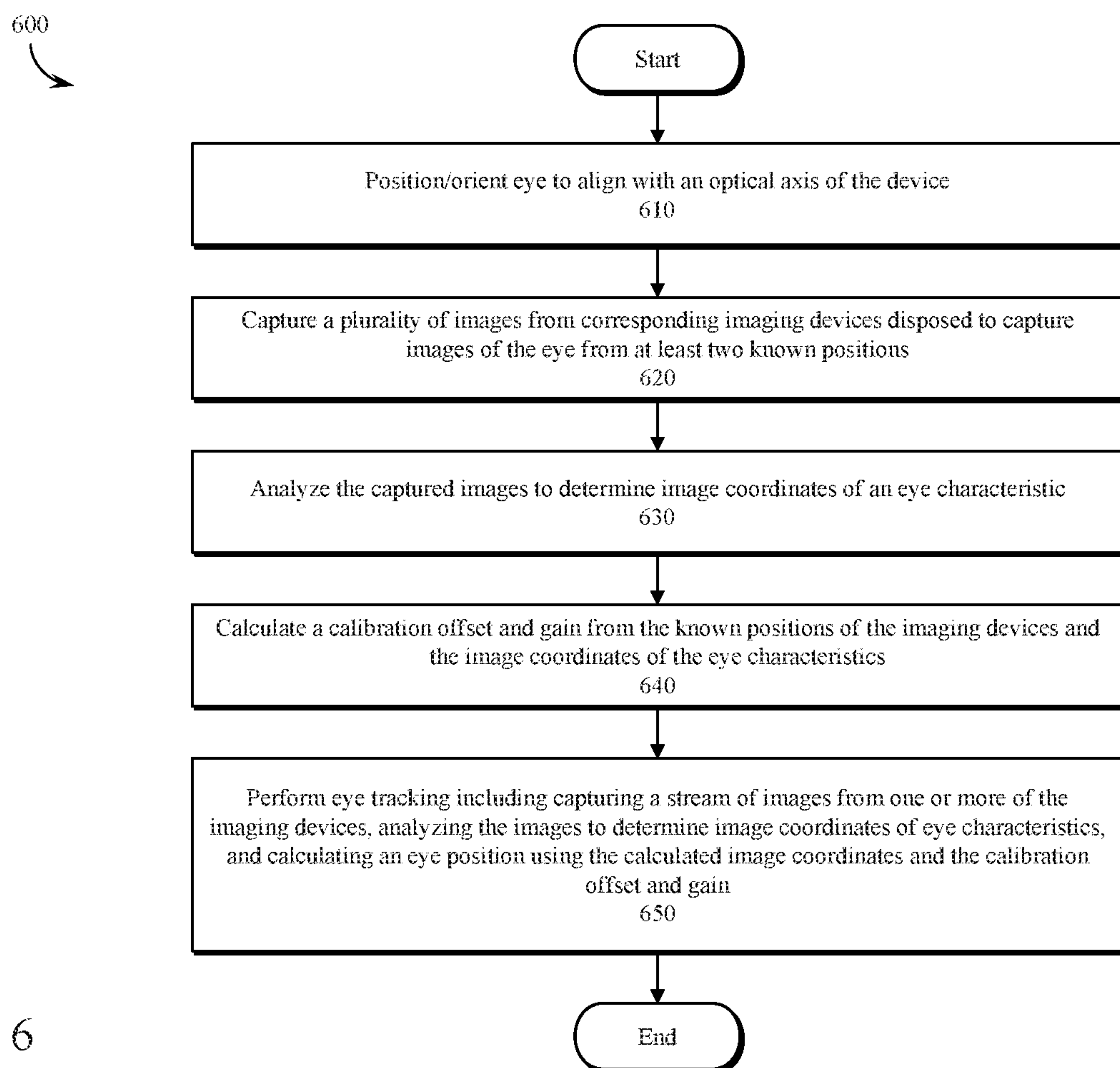


FIG. 6

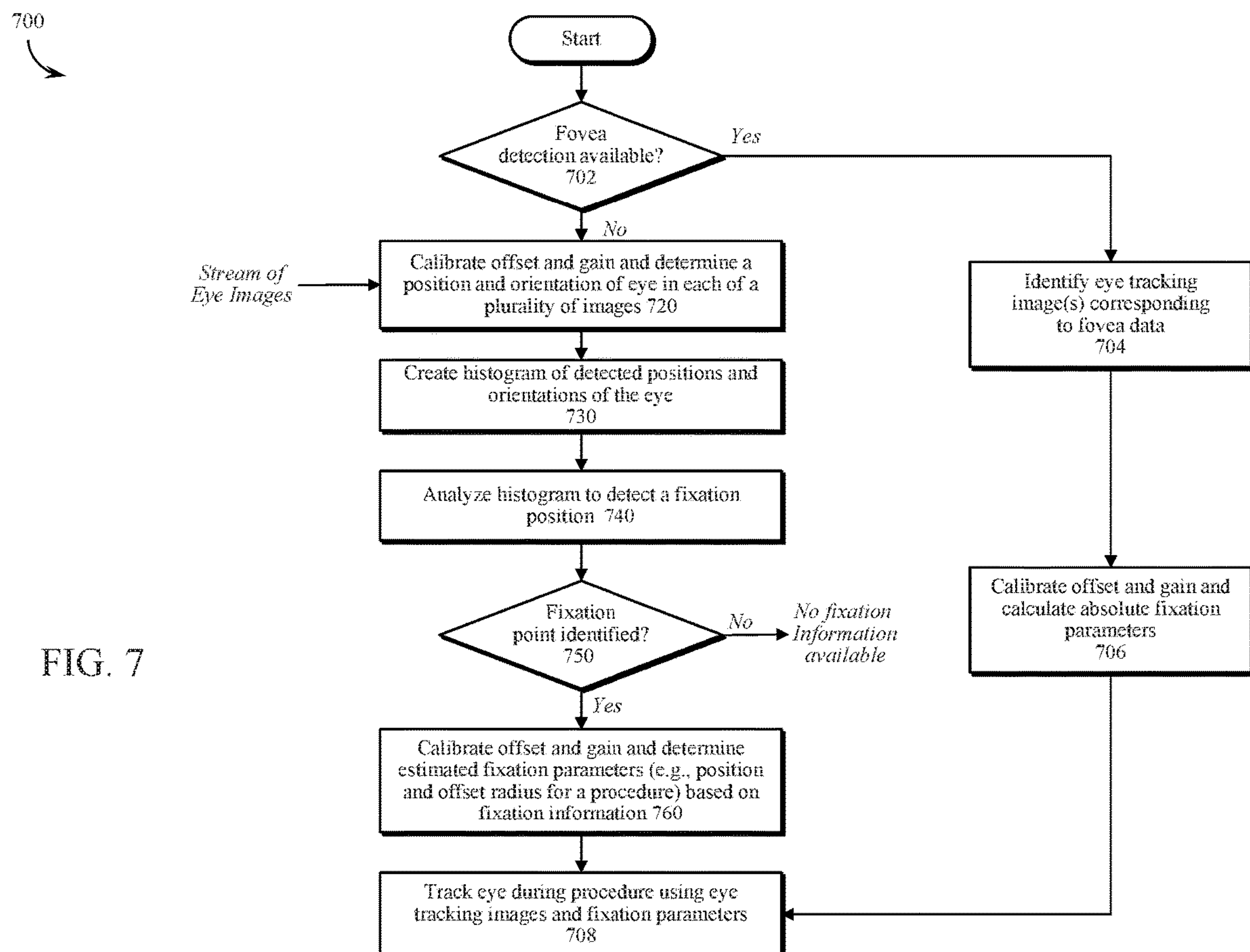


FIG. 7

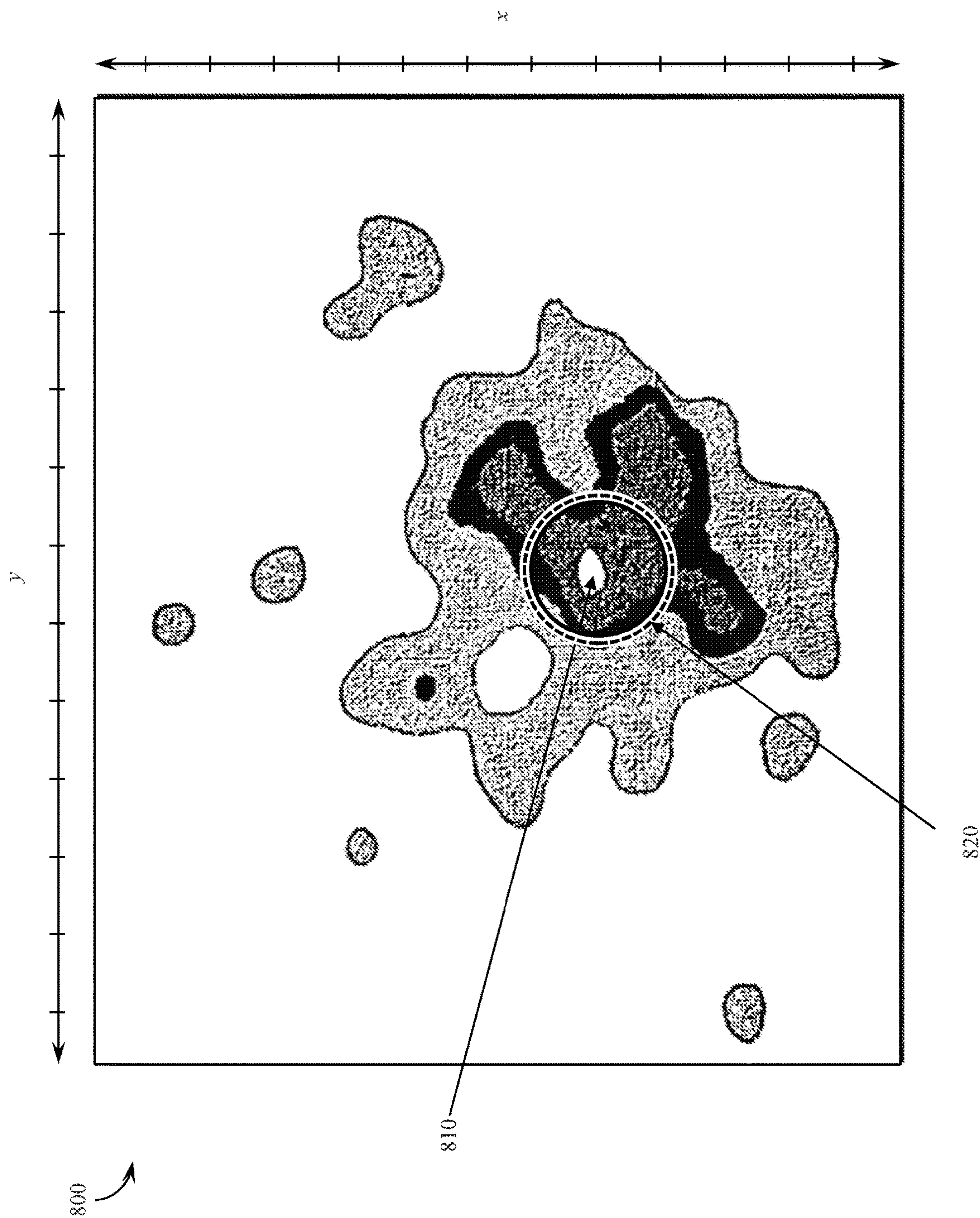


FIG. 8

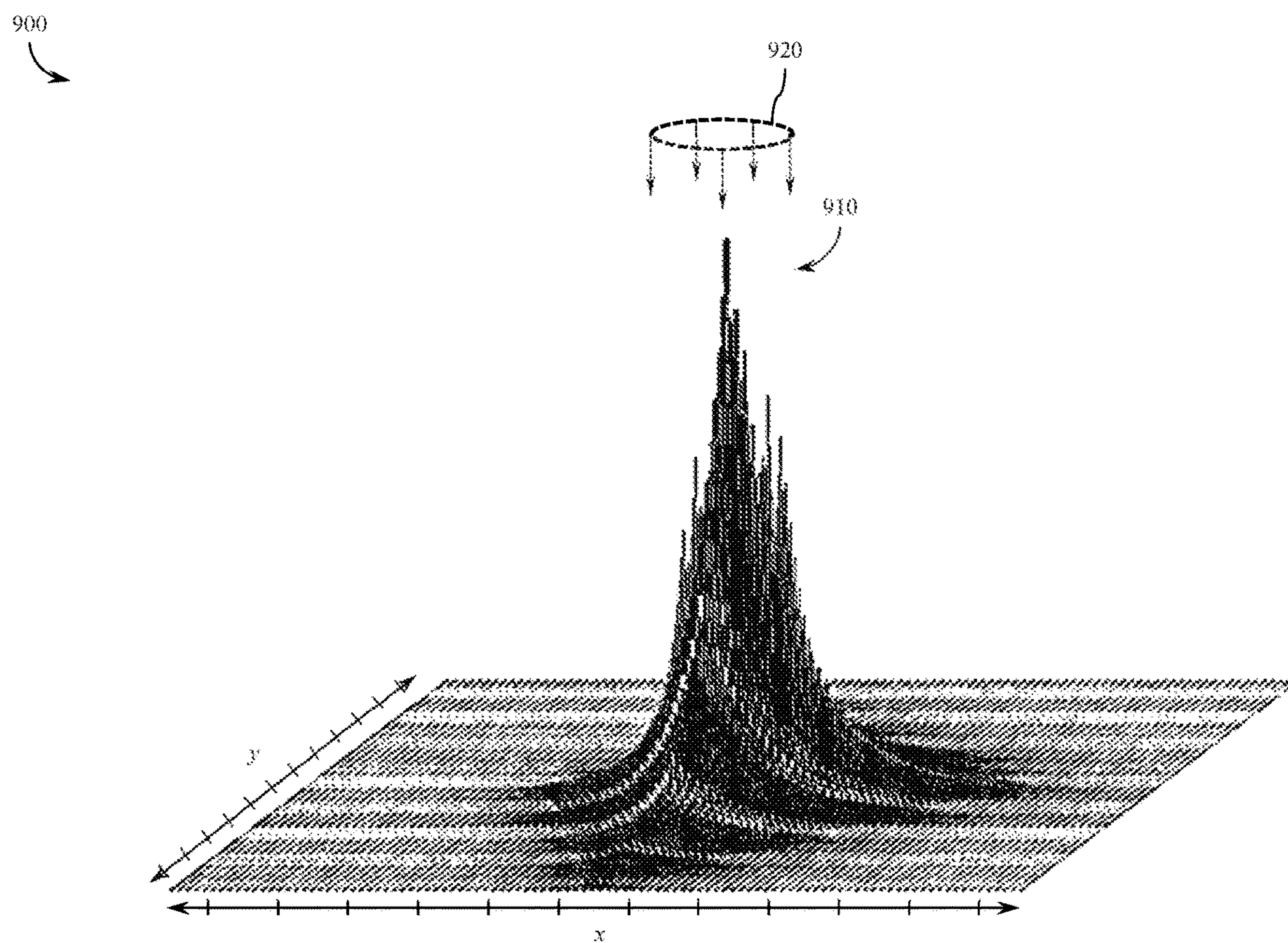


FIG. 9

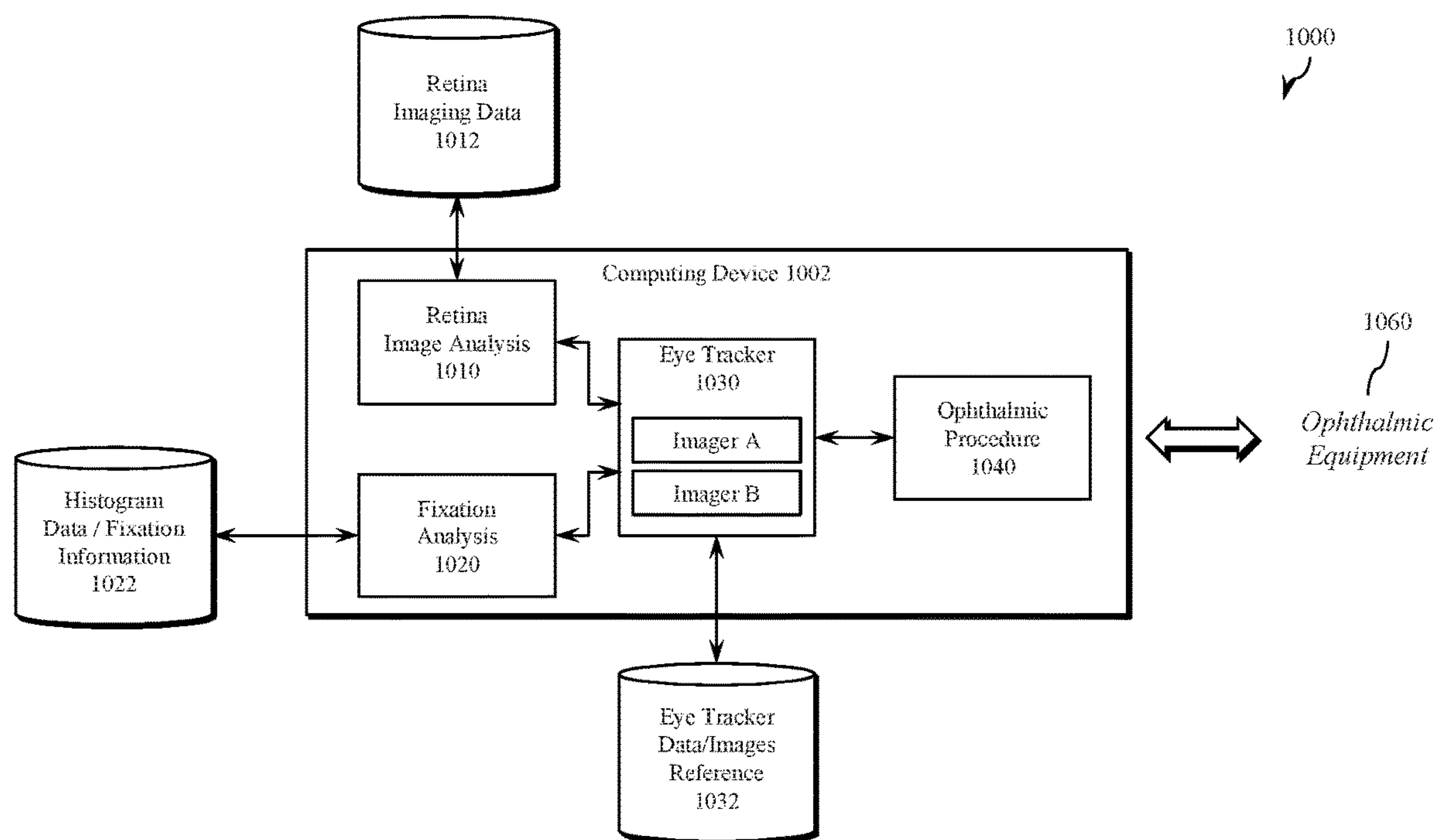


FIG. 10

INSTANT EYE GAZE CALIBRATION SYSTEMS AND METHODS

BACKGROUND

Field of the Disclosure

The present disclosure relates generally to eye tracking systems and methods, and more particularly, for example, to systems and methods for tracking the position and/or orientation of an eye in imaging, tracking, diagnostic and/or surgical systems.

Description of Related Art

A wide variety of ophthalmic devices are used to image, measure, diagnose, track, surgically correct and/or surgically repair a patient's eyes. The operation of an ophthalmic device such as a topography device, a keratometry device, a wavefront analyzer or another device that measures aspects of the eye (e.g., optically, geometrically, etc.), is often based on the assumption that the eye is maintained in a defined position and orientation with respect to the diagnostic device. The patient may be positioned by a human operator of the ophthalmic device and instructed, for example, to look into the device at a target object (e.g., a fixation light) to align the patient's line-of-sight (e.g., the axis along which a person looks at things) to an optical axis of the ophthalmic device. If the patient isn't properly fixated, readings may be inaccurate and/or the system may not be able to properly function.

To ensure accurate data acquisition, the human operator of the ophthalmic device is often tasked with monitoring the patient, leading the patient through an initialization procedure, and/or monitoring feedback from the device during data acquisition to determine whether the patient has been properly fixating on a target object to align the eye. One known technique includes relying on the cooperation of the patient to fixate on a target object as instructed by a device operator. However, existing approaches have many drawbacks including human error in the patient's attempt to fixate (e.g., an elderly patient may be unable to maintain eye position, a patient may lack sufficient concentration to fixate the eye, the patient may not look directly at the target object, etc.) and human error by the operator monitoring the patient during the procedure. In another approach, retina scanning and imaging analysis may be used to track the patient's eye position and orientation, but operation of a retinal imaging system can interfere with a diagnostic procedure. As a result, retina scanning and imaging systems are often shut down or otherwise rendered inoperable for use in eye tracking during a diagnostic procedure performed using the ophthalmic device.

In view of the foregoing, there is a continued need in the art for improved techniques for determining and/or tracking the position and orientation of a patient's eye during an ophthalmic procedure.

SUMMARY

The present disclosure relates generally to an automated method of initializing an eye tracking imaging system. Various embodiments of the present disclosure relate to fully automatic and instantaneous methods of initializing a camera-based gaze tracking system (or other imaging-based eye tracking device) in an ophthalmic device.

In one aspect of the present disclosure, a system comprises an eye tracker configured to capture a first image of an eye from a first location and a second image of the eye from a second location, and a control processor configured to detect a first plurality of eye characteristics from the first image, the eye characteristics having first corresponding image coordinates, detect a second plurality of eye characteristics from the second image, the eye characteristics having second corresponding image coordinates, and determine a calibration offset and a calibration gain based at least in part on the first corresponding image coordinates, the second corresponding image coordinates, the first location and the second location.

The control processor may be further configured to determine an eye fixation position and orientation relative to an optical axis of the eye tracker based at least in part on the first corresponding image coordinates and/or the second corresponding image coordinates, estimate eye fixation parameters based at least in part on the determined eye fixation position and orientation, receive a plurality of images from the eye tracker, and track a current eye position and orientation by analyzing at least one image from the first plurality of images to determine the current eye position and orientation relative to the eye fixation parameters. The eye fixation parameters may comprise a reference position and orientation of the eye when fixated.

The control processor may be further configured to determine the fixation position relative to the optical axis of the eye tracker by constructing and analyzing a histogram of detected eye positions and orientations. Analyzing the histogram may further comprise determining whether coordinates of a relative maximum value comprise a fixation position and orientation, determining whether coordinates of the relative maximum value may further comprise a fixation position and orientation further comprise comparing the relative maximum value with a threshold and/or an average coordinate value of the histogram.

In some aspects of the present disclosure, the system comprises a retina imaging system comprising an optical coherence tomography (OCT) scanner configured to perform a retinal scan, and the eye tracker is further configured to capture a stream of images of the eye during the retinal scan. The retinal imaging system may be configured to capture a plurality of retinal images of the eye, detect whether a fovea is present in one or more of the plurality of retinal images of the eye; and identify a first retinal image from the plurality of retinal images of the eye having the detected fovea. The control processor may be further configured to determine a corresponding image from the stream of images having a temporal proximity to the first retinal image and analyze the corresponding image to determine eye fixation parameters.

In some aspects of the present disclosure, the control processor is further configured to track the eye position and orientation and calculate an offset from the eye fixation parameters and determine if the offset is less than a threshold value. If the offset is less than the threshold value the eye is determined to be fixated and the control processor generates an indication of fixation, and when the offset is greater than the threshold value the eye is determined to be out of alignment and the control processor generates an indication of no fixation.

The control processor may be further configured to perform an eye diagnostic procedure and track eye position using the eye tracker during the eye diagnostic procedure. The system may comprise a diagnostic device configured to perform an eye diagnostic procedure while tracking a posi-

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tion and orientation of the eye using the eye tracker. The diagnostic device may be configured to modify the eye diagnostic procedure based, at least in part, on data representative of eye fixation parameters and a tracked eye position.

In various aspects of the present disclosure, a method comprises capturing a first image of an eye from a first location, capturing a second image of the eye from a second location that is different than the first location, detecting a first plurality of eye characteristics from the first image, the eye characteristics having first corresponding image coordinates, detecting a second plurality of eye characteristics from the second image, the eye characteristics having second corresponding image coordinates, and determining a calibration offset and a calibration gain based at least in part on the first corresponding image coordinates, the second corresponding image coordinates, the first location and the second location.

The method may further comprise capturing a stream of images of the eye, detecting an eye position and orientation in the stream of images based at least in part on coordinates of the detected eye characteristics, the calibration offset and the calibration gain, and determining an eye fixation position and orientation relative to an optical axis. The method may further comprise estimating eye fixation parameters based, at least in part, on the determined eye fixation position and orientation, and tracking the eye position and orientation by analyzing one or more images from the stream of images to determine the eye position and orientation relative to the eye fixation parameters. The eye fixation parameters may comprise a reference position and orientation of the eye when fixated. In some embodiments, the method comprises training a neural network to receive the stream of images and output a determination of an eye position.

In some aspects of the present disclosure, the method further comprises detecting the fixation position relative to the optical axis by constructing and analyzing a histogram of detected eye positions and orientations, which may include determining a relative maximum value.

The method may further include performing a retina imaging scan of the eye using an optical coherence tomography (OCT) scanner, capturing a plurality of retinal images of an eye from the retina imaging scan, capturing a stream of images using an imaging device configured to image a surface of the eye, detecting whether a fovea is present in one or more of the plurality of retinal images, identifying a first retinal image from the plurality of retinal images having the detected fovea, determining a corresponding image from the stream of images having a temporal proximity to the first retinal image, and analyzing the corresponding image to determine eye fixation parameters.

In some aspects of the present disclosure, the method may further comprise tracking an eye position and orientation and calculating an offset from the eye fixation parameters and determine if the offset is less than a threshold value. When the offset is less than the threshold value the eye is determined to be fixated and the control processor generates an indication of fixation. When the offset is greater than the threshold value the eye is determined to be out of alignment and the control processor generates an indication of no fixation.

The method may further comprise performing an eye diagnostic procedure while tracking the position and orientation of the eye using an image capture device, and modifying the eye diagnostic procedure based, at least in part, on data representative of eye fixation parameters and a tracked eye position.

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The scope of the present disclosure is defined by the claims, which are incorporated into this section by reference. A more complete understanding will be afforded to those skilled in the art, as well as a realization of additional advantages thereof, by a consideration of the following detailed description of one or more embodiments. Reference will be made to the appended sheets of drawings that will first be described briefly.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the disclosure and their advantages can be better understood with reference to the following drawings and the detailed description that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures, where showings therein are for purposes of illustrating embodiments of the present disclosure and not for purposes of limiting the same. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure.

FIGS. 1A and 1B illustrate an example eye tracking and imaging system, in accordance with one or more embodiments of the present disclosure.

FIG. 2 illustrates an example eye tracking and imaging system with automatic initialization and calibration, in accordance with one or more embodiments of the present disclosure.

FIG. 3 illustrates an example eye tracking and imaging system, in accordance with one or more embodiments of the present disclosure.

FIG. 4 illustrates an example neural network, in accordance with one or more embodiments of the present disclosure.

FIG. 5 illustrates an example computing system, in accordance with one or more embodiments of the present disclosure.

FIG. 6 illustrates an example operation of an automatic initialization and calibration system, in accordance with one or more embodiments of the present disclosure.

FIG. 7 illustrates a method for estimating an absolute eye position, in accordance with one or more embodiments of the present disclosure.

FIG. 8 illustrates an example heat map of eye position and orientation detected using an eye tracker, in accordance with one or more embodiments of the present disclosure.

FIG. 9 illustrates an example histogram constructed of eye position and orientation data detected using an eye tracker, in accordance with one or more embodiments of the present disclosure.

FIG. 10 illustrates an example system for implementing the method of FIG. 7, in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

The present disclosure relates generally to automated systems and methods of initializing and calibrating eye tracking systems for use during operation of an ophthalmic device. Various embodiments provide fully automated and instantaneous methods of initializing and calibrating a camera-based gaze tracking system that may be used alone or with other components and methods of operating an ophthalmic device.

The systems and methods disclosed herein provide many advantages over conventional systems. Managing eye motion and ensuring patient fixation are factors in the

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operation of many ophthalmic diagnostic devices such as keratometers, corneal topographers and aberrometers, etc. These devices often require the patient to fixate on a specific fixation target inside the instrument to provide accurate readings. If the patient is not properly fixating during the measurement and this is not accounted for, the accuracy of the readings may suffer significantly. For many implementations, the accuracy with which a person can fixate (actively control the gaze on a static target) may be in the order of 1 degree but may be significantly worse than that depending on the condition of the eye (e.g., strong cataract). Even in the cases where a patient is actively fixating, the operation of some ophthalmic devices would be more accurate if the exact gaze profile of the eye is known during the measurement, as this can be directly used to eliminate the measurement noise in the readings introduced by eye gaze motion and inability to steadily fixate.

The improved initialization and calibration techniques disclosed herein allow for more accurate measurement of a patient's eye and may be used in diagnostic systems that determine whether the patient's line-of-sight (also referred to herein as the patient's visual axis) is in alignment with an optical axis of the diagnostic system. The patient's line-of-sight/visual axis may be the axis along which the patient's eye is oriented to look at an object. The systems and methods disclosed herein allow for simpler, shorter and more accurate system initialization and calibration. The diagnostic data acquired in accordance with the systems and methods disclosed herein is more meaningful and accurate than data acquired through conventional approaches.

Referring to FIGS. 1A and 1B, an example eye tracking system for use with an ophthalmic device will now be described in accordance with one or more embodiments. One way to track eye gaze is by analyzing a camera image to compare the position of the pupil in the image to the position of a corneal reflection created from an illumination source that is fixed in space relative to the observing camera. The system illustrated in FIGS. 1A and 1B includes a calibration procedure in which the patient is instructed to fixate on known fixation points that allow the system to calibrate the specifics of the observed eye. As illustrated, an eye tracking system **100** includes image capture components (e.g., a visible light camera) and an illumination source **112A** (e.g., one or more light-emitting diodes (LEDs)) that is in a known fixed position relative to the image capture components. The eye tracking system **100** is configured to image and track an eye **102A** by capturing and analyzing a stream of images of the eye **102A**, such as example camera image **120A**.

The camera image **120A** is analyzed to identify one or more characteristics of the eye **102A**, such as an image of a cornea **122A**, a pupil **124A** and a reflection **126A** of the illumination source **112A**. By identifying one or more eye characteristics in the camera image **120A**, information about the position and orientation of the eye **102A**, such as the eye gaze azimuth GA and the eye gaze elevation GE, may be determined. The camera image **120A** may be analyzed to determine coordinates of alignment and/or offset positions of the eye during a procedure. For example, the camera image **120A** may be analyzed to determine the image coordinates [CRx, CRy] of the corneal reflection **126A** (CR) of the illumination and/or the image coordinates [PCx, PCy] of the pupil **124A** (e.g., the center of the pupil PC).

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The image coordinate differences between the corneal reflection CR and the pupil center PC may be calculated as follows:

$$Dx = CRx - PCx$$

$$Dy = CRy - PCy$$

These image coordinate differences are proportional to the azimuth (GA) and elevation (GE) of the eye gaze:

$$Dx \sim GA$$

$$Dy \sim GE$$

To more accurately derive the eye gaze azimuth GA and the eye gaze elevation GE from Dx and Dy, an offset (ax, ay) and a gain (bx, by) in may be applied to each image coordinate x and y, respectively:

$$GA = ax + bx * Dx$$

$$GE = ay + by * Dy$$

The variables a and b may depend on a variety of factors, including the anatomy of the specific eye being imaged, the setup of camera and illumination source and the optics of the camera, for example. In some embodiments, the determination of a and b may include an initialization procedure during which the patient to be tracked is asked to fixate on a set of targets that stimulate a defined gaze in the eye (e.g., a grid of fixation points). For example, FIG. 1A illustrates a scenario where the patient is asked to focus at a first known fixation point, such as a point proximate to or aligned with the optical axis of the eye tracking system **100**. FIG. 1B illustrates a scenario in which the eye is observing a second known fixation point, such as a point next to the camera. Because the camera position and orientation, eye position and orientation, and the location of the fixation points are known during fixation, the eye gaze azimuth GA and eye gaze elevation GE may be known or estimated for each fixation point. The two camera images **120A** and **120B**, respectively, are analyzed to determine the coordinates, x and y, of one or more eye characteristics in each image (e.g., center of pupil in the image, location of reflection in image). The system of equations may then be solved for a and b initialize and calibrate the system for eye tracking.

The initialization procedure described with reference to FIGS. 1A and 1B may be cumbersome to implement and/or prone to error for some patients. The patient may be instructed, for example, to separately fixate on a grid of 5 or more fixation points to calculate the values of a and b by a statistical or other mathematical analysis (e.g., a least squares analysis). Asking the patient to fixate on a number of targets requires significant patient cooperation and the patient's gaze directed to any one point is subject to error.

Further embodiments of the present disclosure will now be described with reference to FIG. 2. FIG. 2 illustrates an eye tracking system **200** that includes automated initialization and calibration components and procedures that allow for accurate eye gaze tracking in diagnostic systems for keratometry, corneal topography, aberrometry and other uses. Although the systems and methods illustrated in FIG. 2 may be fully automated and reduce/eliminate the need for the patient to run through a cumbersome initialization procedure, various aspects may be used with manual and/or other automatic eye tracking initialization and calibration procedures, including procedures that include an operator guiding a patient to fixate on a series of known fixation points.

The eye tracking system **200** may be implemented in any device that uses accurate fixation of the eye. For example, many ophthalmic devices such as keratometers, topographers and aberrometers rely on accurate eye fixation during

diagnostic procedures. Having accurate information about the actual eye gaze during acquisition of diagnostic data may allow for filtering out of readings with poor fixation, compensating the readings with poor fixation by accounting for the actual gaze orientation, and/or more accurate comparison of diagnostic readings (e.g., corneal topography maps) taken at different points in time and accounting for the gaze difference when comparing the readings.

The eye tracking system **200** includes a first image capture device **201** having a first illumination source **202** and a second image capture device **210** having a second illumination source **212**. The first image capture device **201** and first illumination source **202** may be configured, for example, as a single camera eye tracker adapted to capture images of the patient's eye **220**. The first image capture device **201** may include visible spectrum image capture components arranged to capture an image of the surface of the patient's eye **220** along an optical axis of an ophthalmic device. The second image capture device **210** may include visible spectrum image capture components arranged to capture an image of the surface of the patient's eye **220** from a known angle α . In some embodiments, the second image capture device **210** is the same type of imaging device as the first image capture device **210** (e.g., comprised of the same of similar components, same device model number, etc.) and disposed at the same distance from the eye **220** to generate a second camera image **214** having similar image characteristics as the first camera image **204**.

A processing system **230** controls the operation of the eye tracking system **200** and may include control components **232**, imaging processing components **234**, eye tracking components **236** and system initialization components **238**. The processing system **230** may include one or more systems or devices implemented through a combination of hardware, firmware, and/or software. In some embodiments, the control components **232** are configured to manage the operation of the first image capture device **201** and the second image capture device **210**, including providing instructions to synchronize image capture operations of the image capture devices **201** and **210**. Depending on the system configuration, the first image capture device **201** and second image capture device **210** may be instructed to capture images at the same time and/or sequentially with a short interval between images (e.g., timed to capture two images of the eye **220** in the same position). The image processing components **234** are configured to analyze the captured images to determine one or more eye characteristic, such as a center of a pupil, location of cornea and/or location of reflection in the image. The eye tracking components **236** are configured to track an eye position based on a calibrated measurement of the eye characteristics identified in the one or more image.

The system initialization components **238** are configured to initialize the measurement equations to accurately calculate the eye gaze azimuth GA and the eye gaze elevation GE from the captured image data. In various embodiments, a patient is instructed to fixate on a known fixation point approximating an optical axis of the diagnostic device. The operator may interact with the eye tracking system **200** using a user interface to initiate the eye tracking procedure and guide the user through the initialization processing. In some embodiments, images are captured from each of the image capture devices **201** and **210** and when the patient is fixating on the known point. A first camera image **204** captured by the first image capture device **201** and a second camera image **214** captured by the second image capture device **210** are used in the system initialization routine. The eye fixation

may be determined, for example, based on the judgment of the operator, using a retina imaging system to detect the fovea, through image analysis of the location of the reflection relative to the center of the pupil, through a statistic analysis of multiple images captured over time, and/or through other techniques.

The two images, **204** and **214**, are processed through image processing components **234** to determine eye characteristics for each image. The two sets of eye characteristics represent two different measurements taken when the eye **220** was fixating at a known fixation point. The two sets of equations may then be used to solve for the calibration offset a and gain b, which are used to determine the eye gaze azimuth GA and the eye gaze elevation GE from the image data. By using a second camera to image the eye from a second angle, two images and measurements of the eye may be taken for a single fixation point, allowing the offset and gain to be determined without a cumbersome, multi-fixation point initialization procedure. In other embodiments, one or more additional cameras may be provided at other angles and/or more than one fixation point may be used as necessary to further minimize error.

Various example embodiments of the present disclosure will now be described in further detail with reference to FIGS. 3-10. Referring to FIG. 3, a system **300** in accordance with one or more embodiments includes an eye tracking module **310** (also referred to herein as an "eye tracker") and an optional retina imaging system **330**, which are communicably coupled. The eye tracking module **310** is configured to track the orientation of an eye **302** and may include a first imaging device **312**, second imaging device **313** and one or more illumination components **314**. In some embodiments, the first imaging device **312** and second imaging device **313** are digital cameras or other digital imaging devices configured to image certain features of the eye such as the pupil and corneal limbus (the border between the cornea and the white of the eye, i.e., the sclera) and reflections from one or more of the illumination components **314**. In some embodiments, for example, the illumination components **314** may comprise an LED ring positioned around the camera optics (e.g., coaxial illumination around the imaging device) such that the center of the ring resembles the center of curvature of the cornea.

The system **300** includes control logic **318**, which may include a processor executing stored program instructions configured to perform the functions disclosed herein. In some embodiments, the control logic **318** performs a measurement sequence with a plurality of images captured by the first imaging device **312**. The measurement sequence determines the position and orientation of the eye **302** by using the position of detectable features of the eye **302** in the image data (such as eye tracking data **316**), such as the pupil, limbus, and iris features. The measurement sequence may also determine the position of the reflection of the illumination system at the cornea (such as the reflections **317** comprising a circle pattern of illuminated elements). In some embodiments, during the measurement sequence, the position and orientation of the eye **302** is continually determined using the captured images. The control logic **318** may also perform an initialization and calibration sequence (e.g., the sequence described with reference to FIGS. 1A, 1B and/or 2) including calculating a calibration offset and gain from a pair of images captured from the imaging devices **312** and **313**, respectively, to accurately calculate the eye position and orientation from the captured image data.

The control logic **318** may be embodied in the eye tracking module **310**, the retina imaging system **330** and/or

in other system components. The control logic **318** is configured to detect relative eye movement during operation of the eye tracking module **310**, which may include detecting and tracking eye features (e.g., detect the pupil) from the captured images and knowledge of the illumination source position. For example, detecting and calculating an offset of the center of the pupil and an offset of the cornea curvature may provide information about the relative gaze of the eye.

The optional retina imaging system **330** may include any device or system for imaging the retina of the eye **302**. The retina imaging system **330** may be implemented as a retina optical coherence tomography (OCT) system, a retina optical system, or similar system for imaging the retina. In some embodiments, the retina imaging system **330** and/or the control logic **318** is configured to detect the fovea of the patient at least once during the full measurement sequence. As a result, the retina imaging system **330** does not need to be active during the full diagnostic sequence (e.g., for technical or safety reasons) and may be shut down or paused as desired.

The fovea often appears as depression in the retina which may be detected in certain retina imaging systems. In various embodiments, the retina imaging system **330** generates retina imaging data **332**, such as a retina OCT image **334** and/or a fundus image **336**. The retina imaging system **330** may comprise retina OCT scanning system, a fundus imaging system, or other similar device. If the patient is fixating on a target object associated with the system **300**, the fovea will be present in the center of the optical axis of the retinal imaging device. The retina imaging device may only need to scan the center part around the optical axis of the device. If the patient is fixating, then the fovea will be present in the retina imaging data. In some embodiments, the retina imaging device is configured to image the back of the eye for fovea detection. If the system needs to image a different part of the eye (e.g., high resolution scan of the cornea), then the fovea will not be visible in the image and the eye tracking module **310** will be used to track the eye position and rotation.

The system **300** coordinates the processing of information relating to the orientation of the eye from the imaging devices **312** and **313** of eye tracking module **310** (such as eye tracking data **316**, including detected illumination source reflections **317**, captured from each image capture component). The system **300** may further coordinate the eye tracking data **316** with the information from the optional retina imaging system **330** (such as retina imaging data **332**). In operation, if the system **300** (e.g., via the retina imaging system **330** and/or control logic **318**) detects the fovea in a certain area of the retina imaging data **332**, then the corresponding orientation of the eye is known to the system **300**. With this information, the system **300** may further determine if the patient is fixating correctly even in phases of the measurement in which retina imaging is not available. The fixation information may be used by the eye tracking module **310** to identify images (e.g., images of the eye when fixating) for used in an initialization and calibration process. The calibrated eye tracking module **310** may then be used to accurately calculate the eye position and orientation from captured images.

The eye tracking module **310** may be configured to image and the track eye position and eye rotation at the same time as the retinal imaging. In some embodiments, the captured images include associated temporal characteristics such as a timestamp, frame reference (e.g., 10 frames ago), or other information allowing synchronization of the retinal images and the images captured from the first imaging device **312**

and the second imaging device **313**. After the fovea is detected, the fovea detection information, which may include a corresponding temporal characteristic and an indication of whether the fovea was detected may be provided to control logic **318**, eye tracking module **310**, and/or other system components.

In some embodiments, the analysis of the position and orientation of the eye **302** includes a method that compares the orientation/position of the eye at the time the fovea was visible with the retina imaging system with current eye tracking data. The system **300** may be used, for example, in a diagnostic procedure that includes a measurement sequence. By tracking the eye position and orientation during a procedure using the eye tracking module **310**, measurement data may be gathered and analyzed with the corresponding eye tracking data. In one embodiment, measurement data acquired when the eye **302** was fixated (e.g., when the eye position is within an acceptable offset from a fixation position) is considered valid and used for further diagnostics/analysis and measurement data acquired when the eye **302** was not fixated (e.g., when the eye position is outside an acceptable offset from a fixation position) may be ignored and/or discarded.

In various embodiments, the system **300** uses the fovea detection information to establish reference fixation information, which may include a certain orientation of the pupil in relation to the cornea. The eye tracking module **310** can receive fovea detection information (e.g., fixation determined at particular time or other temporal reference), retrieve one or more corresponding images from the same timeframe, and analyze the captured image(s) to determine the specific relationship between the pupil and the cornea center during fixation. The system may be initialized and calibrated using the captured images to determine a calibration offset and gain for more accurate measurement results. The eye position may then be tracked by comparing the eye position and orientation in newly captured images with the eye position and orientation from reference images. This allows the retina imaging system **330** to image another part of the eye **302** (or operation of other ophthalmic equipment as desired) while the eye tracking module **310** confirms that the eye is fixating. The eye tracking module **310** may provide fixation information to the retina imaging system **330** indicating whether a current scan was taken while the eye was fixating (within a range of error relative to the reference data) or whether the current scan was taken while the was not fixating, such as when the offset between the current eye position and the reference eye position exceeds a threshold value.

During operation of the system **300** the retina imaging system **330** may be shut down during a diagnostic or other procedure such that retina imaging data **332** is no longer generated. If the fovea has been previously detected by the retina imaging system **330** at least one time, the system **300** can continue to provide the device operator information about the patient's eye fixation, even during phases of the procedure in which no retina imaging is available. For example, the system **300** may compare the current eye position and orientation captured using the eye tracking module **310** to the eye position and orientation determined when the retina imaging system **330** detected the fovea. The eye tracking module **310** may provide an indication to the device operator through one or more visual (e.g., indicator light, status information on a display screen) or audible cues (e.g., beeps). The eye tracking module **310** may further provide fixation information to other components of the system **300**, for example, to control operations that require

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eye fixation and/or to validate/invalidate acquired data. It will be appreciated that the systems and methods described in FIG. 3 are example implementations of various embodiments, and the teachings of the present disclosure may be used in other eye tracking systems, such as systems or devices using an illumination system generating purkinje reflections and a camera to capture digital images of the eye.

To aid in determining whether the eye is fixated, the control logic 318 may be configured to determine a current position and orientation of the eye and calculate an offset to determine whether the eye is sufficiently fixated on the desired object. In one embodiment, one or more thresholds may be determined and any offset lower than a corresponding threshold will result in a determination that the eye is fixated. In some embodiments, the fixation determination and threshold are application dependent and different offsets may be acceptable for difference implementations.

In some embodiments, the retina imaging system 330 identifies a timeframe (e.g., a period of time, one or more images, a sequential index value, etc.) in which the fovea was detected, allowing the eye tracker to identify corresponding eye tracking imagery that was taken at the same, or approximately the same time. The eye tracking module 310 and/or control logic 318 may then perform an initialization and calibration procedure to determine a calibration offset and gain which may be used to accurately calculate the eye position and orientation from the captured images. The eye tracking module 310 may then determine a reference position of the eye associated with the fixation position, including relative position of the pupil and cornea. The eye fixation information may be immediately used by the system 300 to track the eye position and orientation and/or stored and retrieved for use by the system 300 at a later time. For example, eye fixation information may be determined and stored for a patient and retrieved for use by the system 300 (or similar system) for subsequent procedures for the patient or for offline analysis of captured images.

While the retina imaging system 330 is performing other scans and/or other ophthalmic components are in operation, the eye tracking module 310 captures a stream of images and analyzes the eye position and alignment with reference to the position and orientation determined from the reference image(s). This analysis may be performed in real time during a procedure and/or offline (e.g., when analyzing previously captured data). The current images are compared to the reference image(s) and an offset is calculated. If the offset is less than a threshold then the eye is fixating and the corresponding retina images are accurate. If the offset is greater than the threshold then the eye is not fixating and the corresponding retina images may be flagged, discarded or other action taken.

In some embodiments, the eye tracking module 310 continually images the eye throughout the procedure. For each frame, the pupil position may be detected in the image based, at least in part, on where reflections are detected in the image stream. In various embodiments, the information tracked and recorded may include one or more of the image, image features extracted from the image, image properties, pupil location and/or reflection position in the image. The eye tracking system and retina imaging system are synchronized such that for each retina scanned image, one or more corresponding eye tracker images may be identified. In one embodiment, there is a one-to-one correspondence. In other embodiments, the images are synchronized through a timestamp or other synchronization data associated with the captured images.

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It will be appreciated that while the eye tracking module 310 and optional retina imaging system 330 are described as separate components, the system 300 may comprise a diagnostic device with various subcomponents including the eye tracking module 310, the retina imaging system 330 and other subcomponents. In some embodiments, a central processor may be provided to control the operation of the system 300, synchronize and control communications between the two systems and perform other system functions. Analysis of the eye position and orientation may be performed in real-time by the system 300, or later after the procedure is complete. Online, the system 300 may provide feedback to the patient and operator. Offline, the system 300 and/or other systems may perform more a complex analysis to achieve more accurate scans and results.

In some embodiments, the system 300 may comprise a larger diagnostic device that includes two or more cameras (e.g., for imaging the surface of the eye), and a second component for measuring the retina. The system 300 may include a plurality of sensors configured to image the eye to create a 3-D eye model. A first sensor system may include two or more cameras to recover the cornea shape and do the eye tracking. A second sensor system may include a wavefront sensor that measures the wavefront of the eye (optical parameters of the eye). A third sensor may include an OCT system that can measure distances between different refractive surfaces of the eye. The OCT may include multiple modes and resolutions including a full eye mode, half-eye mode (front of eye) and cornea mode (having higher resolution).

Sensor data may be provided to a processor (e.g., as illustrated in FIG. 5) which collects and stores the data in a memory. The processor may use a fusion algorithm to derive a 3D model of the eye comprising a parameterized model that incorporates the various sensor data. The 3D model may be used, for example, for cataracts and corneal refractive surgery planning. The data may be used for ray tracing, to assist in intraocular lens (IOL) implant placement in the eye, etc. The fovea detection and eye tracking innovations described herein may be used with any diagnostic device or instrument that includes a device that scans through the retina. Eye tracking may be implemented in a keratometer, biometer, wavefront measurement device, and other devices including a digital camera and illumination.

In various embodiments, the absolute eye orientation utilizes a device that scans through the retina, such as an OCT device, which may include biometers and other devices that (i) provide retina scanning and other diagnostic modes, and (ii) other sensors that perform other input functions. The system disclosed herein may be used with more components, different components, and fewer components in various embodiments.

Advantages of the present application will be understood by those skilled in the art. The systems and methods disclosed herein provide automated initialization and calibration of eye tracking information. Eye tracking may be performed when the patient is fixating and not fixating, independent of the patient (e.g., not relying on the patient's cooperation). The eye tracking information is collected and provided to a processor, which enables further analysis. Other sensor data may be acquired and validated by backtracking through the data to adjust for a known or projected orientation based on the eye tracking data. For example, an eye position may be determined and provided to the retina imaging system for use in analyzing the scan data. The ability to flag whether the patient is fixation or not fixating is valuable for many system operations and the accuracy

provided by the initialization and calibration of the present disclosure allows a system to more accurately determine fixation times/intervals and/or adjust for calculated offsets. The ability to determine a degree of fixation allows the system to adapt for use in variety of implementations. Storing the captured data for later retrieval and analysis allows for further calculations offline and more complex analysis and options, such as through use of complex neural networks or other analytical processes.

In one embodiment, the control logic is configured with a reference point and a threshold which are used to filter out unreliable sensor data. For example, the system may be configured such that a small gaze change (e.g., 0.03 degrees of offset) may be okay, but a larger gaze change will indicate unreliable data that should be filtered out. In some embodiments, the sensor data acquired during fixation may be averaged together or otherwise combined. In other embodiments, the acquired data may be analyzed along with eye position and orientation information by calculating an eye position during acquisition using a calculated offset and known eye position and orientation at a reference point. In some embodiments, the various sensor and data inputs and calculations may be processed using a fusion engine to generate desired output data.

In various embodiments, one or more neural networks may be used for image and data analysis, such as to determine whether the eye is fixated on a target object. FIG. 4 is a diagram of an example multi-layer neural network 400 according to some embodiments. The neural network 400 may be representative of a neural network used to implement at least some of the logic, image analysis and/or eye fixation determination logic as described herein. The neural network 400 processes input data 410 using an input layer 420. In some examples, input data 410 may correspond to image capture data and captured retina image data as previously described herein. In some embodiments, the input data corresponds to input training data used to train neural network 400 to make fixation, orientation and/or other determinations.

Input layer 420 includes a plurality of neurons that are used to condition input data 410 by scaling, range limiting, and/or the like. Each of the neurons in input layer 420 generates an output that is fed to the inputs of a hidden layer 431. Hidden layer 431 includes a plurality of neurons that process the outputs from input layer 420. In some examples, each of the neurons in hidden layer 431 generates an output that collectively are then propagated through one or more additional hidden layers that end with hidden layer 439, as illustrated. Hidden layer 439 includes a plurality of neurons that process the outputs from the previous hidden layer. The outputs of hidden layer 439 are fed to an output layer 440. Output layer 440 includes one or more neurons that are used to condition the output from hidden layer 439 by scaling, range limiting, and/or the like. It should be understood that the architecture of neural network 400 is representative only and that other architectures are possible, including a neural network with only one hidden layer, a neural network without an input layer and/or output layer, a neural network with recurrent layers, and/or the like.

In some examples, each of input layer 420, hidden layers 431-439, and/or output layer 440 includes one or more neurons. In some examples, each of input layer 420, hidden layers 431-439, and/or output layer 440 may include a same number or a different number of neurons. In some examples, each of the neurons takes a combination (e.g., a weighted sum using a trainable weighting matrix W) of its inputs x , adds an optional trainable bias b , and applies an activation

function f to generate an output a as shown in the equation $a=f(Wx+b)$. In some examples, the activation function f may be a linear activation function, an activation function with upper and/or lower limits, a log-sigmoid function, a hyperbolic tangent function, a rectified linear unit function, and/or the like. In some examples, each of the neurons may have a same or a different activation function.

In some examples, neural network 400 may be trained using supervised learning where combinations of training data that include a combination of input data and a ground truth (e.g., expected) output data. Differences between the generated output data 450 and the ground truth output data may be fed back into neural network 400 to make corrections to the various trainable weights and biases. In some examples, the differences may be fed back using a back-propagation technique using a stochastic gradient descent algorithm, and/or the like. In some examples, a large set of training data combinations may be presented to neural network 400 multiple times until an overall loss function (e.g., a mean-squared error based on the differences of each training combination) converges to an acceptable level. The trained neural network may be stored and implemented in an ophthalmic device (e.g., system 300 of FIG. 3) for real time classification of captured images (e.g., as fixated or not fixated), and/or stored and implemented in an offline system for analysis of the captured data.

FIG. 5 illustrates an example computing system that may include one or more components and/or devices of systems 100, 200 and 300, including an implementation of an eye tracking module 310 and an optional retina imaging system 330. The computing system 500 may include one or more devices in electrical communication with each other, including a computing device 510 that includes a processor 512, a memory 514, communications components 522 and user interface devices 534.

The processor 512 may be coupled to various system components via a bus or other hardware arrangement (e.g., one or more chipsets). The memory 514 may include a read only memory (ROM), a random-access memory (RAM), and/or other types of memory (e.g., PROM, EPROM, FLASH-EPROM, and/or any other memory chip or cartridge). The memory 514 may further include a cache of high-speed memory connected directly with, in close proximity to, or integrated as part of processor 512. The computing device 510 may access data stored in ROM, RAM, and/or one or more storage devices 524 through a cache for high-speed access by the processor 512.

In some examples, memory 514 and/or storage device 524 may store one or more software modules (e.g., software modules 516, 518, and/or 520), which may control and/or be configured to control processor 512 to perform various actions. Although the computing device 510 is shown with only one processor 512, it is understood that processor 512 may be representative of one or more central processing units (CPUs), multi-core processors, microprocessors, microcontrollers, digital signal processors (DSPs), field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), graphics processing units (GPUs), tensor processing units (TPUs), and/or the like. In some examples, computing device 510 may be implemented as a stand-alone subsystem and/or as a board added to a computing device or as a virtual machine.

To enable user interaction with system 500, the computing device 510 includes one or more communication components 522 and/or one or more user interface devices 534 facilitating user input/output (I/O). In some examples, the one or more communication components 522 may include

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one or more network interfaces, network interface cards, and/or the like to provide communication according to one or more network and/or communication bus standards. In some examples, the one or more communication components 522 may include interfaces for communicating with computing device 510 via a network 580, such as a local area network, a wireless network, the Internet or other network. In some examples, the one or more user interface devices 534 may include one or more user interface devices such as keyboards, pointing/selection devices (e.g., mice, touch pads, scroll wheels, track balls, touch screens), audio devices (e.g., microphones and/or speakers), sensors, actuators, display devices, and/or other input/output devices.

According to some embodiments, the user interface devices 534 may provide a graphical user interface (GUI) suitable for aiding a user (e.g., a surgeon and/or other medical personnel) in the performance of the processes disclosed herein. The GUI may include instructions regarding the next actions to be performed, diagrams of annotated and/or un-annotated anatomy, such as pre-operative and/or post-operative images of an eye, requests for input, and/or the like. In some examples, the GUI may display true-color and/or false-color images of the anatomy, and/or the like.

The storage device 524 may include non-transitory and non-volatile storage such as that provided by a hard disk, an optical medium, a solid-state drive, and/or the like. In some examples, the storage device 524 may be co-located with computing device 510 (e.g., a local storage device) and/or remote from system 500 (e.g., a cloud storage device).

The computing device 510 may be coupled to one or more diagnostic, imaging, surgical and/or other devices for use by medical personnel. In the illustrated embodiment, the system 500 includes an ophthalmic device 550, an eye tracker 560 and an optional retinal imager 570, which may be embodied in one or more computing systems, including computing device 510. The ophthalmic device 550 includes a user interface 554 for controlling and/or providing feedback to an operator conducting a procedure on a patient's eye 552. The ophthalmic device 550 may include devices for imaging, measuring, diagnosing, tracking, and/or surgically correcting and/or repairing the patient's eye 552.

The ophthalmic device 550 is communicably coupled to the eye tracker 560 (such as eye tracking module 310 of FIG. 3), which receives eye imaging data from the ophthalmic device, and provides status information of the position and alignment of the eye 552 during a procedure. The eye tracker 560 includes two or more imagers (e.g., imager A and imager B) positioned at known locations relative to an optical axis of the ophthalmic device 550. The eye tracker 560 is configured to perform an initialization and calibration procedure that may be fully or partially automated. The calibration procedure includes instructing each of imager A and imager B to capture one or more images of the eye 552 while the eye is fixating, and calculating a calibration offset and gain. The eye tracker 560 may then capture images of the eye 552, analyze the captured images for one or more eye characteristics, and calculate an eye gaze azimuth GA and an eye gaze elevation GE using the calibration offset and gain. The optional retinal imager 570 is communicably coupled to both the ophthalmic device 550 and the eye tracker 560 and configured to capture a retinal image of the eye 552 for use in an ophthalmic procedure and for detection of the fovea for use in fixation tracking.

In various embodiments, the memory 514 includes an optional retina image analysis module 516, an eye tracker module 518, and an ophthalmic procedure module 520. The retina image analysis module 516 includes program instruc-

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tions for instructing the processor 512 to capture retina images using the retinal imager 570 and/or analyze captured retina images. The retina image analysis module 516 may include a neural network trained to receive one more captured retina images (e.g., a captured image, a real-time stream of retinal images, stored retina images, etc.), extract relevant image features, and detect the presence or absence of the fovea (e.g., output a classification indicating fovea detection, output a probability of proper eye position and/or alignment, etc.).

The eye tracker module 518 includes program instructions for instructing the processor 512 to capture images of the eye 552 using the eye tracker 560 and/or analyze captured images. The eye tracker module 518 may include one or more neural networks trained to receive one or more captured images (e.g., a captured image, a real-time stream of eye images from eye tracker 560, image pairs from image A and image B, stored eye images, etc.), extract relevant images features, and output eye tracking information (e.g., output an indication of eye alignment, output a probability of proper eye position and/or alignment, output an offset of the eye from a proper position and alignment, etc.).

In various embodiments, the eye tracker module 518 is configured to determine a reference eye position based on alignment data received during fixation of the eye 552 on a known fixation point. For example, the eye tracker module 518 may receive fovea detection information from the retina image analysis module 516, which is used to identify corresponding images from the eye tracker 560 that show the eye 552 in proper alignment. The eye tracker module 518 may receive fixation information from other sources, including operator feedback, statistical analysis, image analysis, and other sources available to the system 500. The eye tracker module 518 is further configured to automatically calibrate eye position calculations by a process including capturing an image from imager A and an image from imager B during fixation, determining at least one eye characteristic in each image, comparing image coordinates of the eye characteristic(s) in the two images, and calculating a calibration offset and gain for use in future eye position calculations. The eye tracker module 518 is further configured to analyze images captured by the eye tracker 560 and output eye tracking information with reference to the reference image and/or calculated position.

The ophthalmic procedure module 520 includes program instructions for instructing the processor 512 to conduct an ophthalmic procedure and may include user input and output during the procedure through user interface 554, and analysis of captured data. In some embodiments, the ophthalmic procedure module 520 includes a trained neural network for analyzing data captured during the procedure. The ophthalmic procedure module 520 receives eye tracking information from the eye tracker module 518, which may include an alignment status within an acceptable offset threshold, offset data, and/or other information. In some embodiments, the ophthalmic procedure module 520 is configured to operate when the patient's eye 552 is in an acceptable alignment position and provide an indication (e.g. a sound such as a beep, a visual indication such as a flashing light, etc.) through the user interface 554 to an operator of the ophthalmic device 550 when the patient's eye is out of alignment.

The system 500 may store captured retinal, eye tracking and ophthalmic procedure data for later processing, including online processing (e.g., during a subsequent procedure) and offline processing. The storage device 524 may store retinal images data 526 captured for a patient, which may

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include a patient identifier, a stream of captured images, temporal information (e.g., a time stamp, sequential index, etc.) and/or information on whether the fovea was detected in an image. The storage device **524** may also store eye tracker data **528**, which may include a patient identifier, a stream of captured images, temporal information (e.g., a time stamps, sequential index, etc.), whether the captured image corresponds with a detected fixation period and/or information providing a reference position of an eye during fixation, and/or calibration offset and gain information. The storage device **524** may also store procedure data **530** captured for a patient during the procedure, including a patient identifier, a stream of data captured during the procedure (e.g., images, data readings, data calculations, etc.), temporal information (e.g., a time stamp, sequential index, etc.), offset information calculated for the eye position at a point in the procedure, and/or whether the eye was fixated at a time during the procedure.

The computing device **510** may communicate with one or more network servers **582** providing one or more application services to the computing device. In some embodiments, the network server **582** includes a neural network training module **584** for training one or more of the neural networks using a training dataset **586**, which may include labeled images. For example, the retina image analysis module **516** may include a neural network trained using a set of retina images labeled to identify the presence and/or absence of the fovea. The eye tracker module **518** may further include a neural network trained using a set of captured eye images and reference data, labeled to identify an offset of the image with respect to the reference data. The ophthalmic procedure module **520** may include a neural network trained using a set of data representing data captured during a procedure, including alignment and/or offset data from the eye tracker module **518**.

Referring to FIG. 6, an example embodiment of a process **600** for initializing and calibrating an ophthalmic device will now be described. In step **610**, the patient is positioned at the ophthalmic system and directed to focus on a target object to align the patient's line of sight with an axis of alignment of the ophthalmic device. In one embodiment the patient's retina is analyzed to confirm the patient is properly fixating. For example, system may include a retina imaging system configured to scan the retina, acquire scanned retina data, and analyze the acquired data to detect the fovea. In some embodiments, the system operator may provide feedback to the system based on the operator's determination of whether the patient is fixating. In other approaches, image data may be acquired during the fixation procedure and analyzed to determine fixation (e.g., through an analysis of histograms or other image data).

In step **620**, a plurality of images of the surface of the eye are captured from corresponding imaging devices disposed to capture images from at least two known positions. For example, in the systems of FIGS. 2 and 3, two cameras are used to capture a pair of images of the eye, each from a different known position. In various embodiments, the images are captured simultaneously or sequentially across a short time interval to capture a current position and orientation of the eye.

In step **630**, the captured images are analyzed to determine image coordinates of one or more eye characteristic. The eye characteristic may include a center of the pupil detected in the images, center of a cornea detected in the images, location of reflection from an illumination source detected in the images, or other eye characteristic. In some embodiments, the image coordinates represent (x,y) coordi-

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nates of a pixel location within each image, which may be mapped to a real-world position to determine the eye position and orientation.

In step **640**, a calibration offset and gain are calculated from the known positions of the imaging devices and the image coordinates of the eye characteristics. For example, image coordinate differences between two eye characteristics (e.g., pupil center PC and corneal reflection CR location) may correspond to the azimuth ($Dx=CRx-PCx$) and elevation ($Dy=CRy-PCy$) of the eye gaze. To more accurately derive the eye gaze azimuth GA and the eye gaze elevation GE from the coordinate differences (e.g., Dx and Dy), a calibration offset value and gain value may be used:

$$GA=ax+bx*Dx$$

$$GE=ay+by*Dy$$

The systems of equations from two imaging devices is used to solve for the calibration offset a and calibration gain b values.

In step **650**, the system performs eye tracking during an ophthalmic procedure. The eye tracking includes capturing a stream of images from one or more of the imaging devices, analyzing the images to determine image coordinates of detected eye characteristics, and calculating an eye position and rotation using the calculated image coordinates and calibration offset and gain values.

In some embodiments, eye tracking may be performed to determine whether the eye is properly positioned and aligned during diagnostics. The eye tracking system may analyze captured images of the eye during the diagnostics and determines a current position and rotation based on the captured images. The current position and rotation is compared with the fixation position and rotation to determine an offset. If the offset is below an error threshold, then the eye is determined to be in proper position and alignment for measurement. If the offset is above an error threshold, then the diagnostic process and/or the system operator may be notified that the eye is out of alignment allowing the operator to pause the diagnostic procedure and instruct the patient to reposition the eye, allowing for the associated measurement data to be determined valid/invalid, or allowing for other actions to be taken. In some embodiments, the data acquired during the eye diagnostic procedure is stored in a storage device and the data acquired during the eye tracking procedure is stored in a storage device, for subsequent processing and analysis. In one embodiment, the patient's data is tracked in addition to the fovea information and may be verified using fovea information where available. In this manner, a range of values and an average fixation position may be determined.

In various embodiments, the ophthalmic system is configured to determine an absolute fixation position of the eye. In some systems, retina imaging information and/or fovea detection information may be used if available. In other systems, absolute fixation position may be determined through one or more of operator feedback, detailed initialization procedures, image analysis, statistical analysis and/or other methods.

In various embodiments, a fixation analysis is performed by detecting eye positions in a stream of images captured from a camera and analyzing the results to estimate an absolute fixation position. The analysis may include a statistical analysis using a histogram of eye positions determined from the captured images. If the histogram shows a clear maximum according to the analysis, then the method can estimate the absolute fixation position. If the histogram

shows no clear maximum, then the method may indicate that no fixation has been detected. In some embodiments, the analysis of the captured images may include a comparison between the patient's eye and other eyes in known positions (e.g., use of a neural network trained using a set of labeled training images), historical fixation information for the patient, image analysis (including tolerances/thresholds), and/or other analysis of available information. In some embodiments, the method may rely on the operator and patient to properly fixate the patient's eye. In some embodiments, the method may address scenarios in which the operator and/or patient error causes the images to not reflect fixation (e.g., if the patient fixates intentionally on a wrong spot, or the operator doesn't properly instruct and/or monitor the patient).

Embodiments of systems and methods for eye tracking in which a retina OCT scan is not available and/or the fovea has not been reliably detected before the procedure will now be described with reference to FIGS. 7-10. As previously discussed, an accurate measurement of the eye using an ophthalmic device may start with an alignment of the patient's line-of-sight (the patient's visual axis) to a certain optical axis of the ophthalmic device. The line-of-sight in this context may be the axis along which the patient looks at things. The resulting diagnostic data and/or other results of the ophthalmic procedure may be unreliable during the periods in which the patient was not properly fixating.

The absolute eye fixation position may be used by the ophthalmic device to provide feedback to a device operator regarding whether the patient is fixating (or not properly fixating) on a certain optical axis of a diagnostic device during a procedure (e.g., a measurement procedure). The ophthalmic device may use the absolute eye fixation position during the procedure to identify periods during which the patient is properly fixating. The system may also use the absolute eye fixation position to determine whether data acquired during a procedure is reliable and/or unreliable data based at least in part on whether the patient was determined to be fixating during data acquisition.

Referring to FIG. 7, an embodiment of a method 700 for estimating absolute eye fixation will now be described. The method 700 is performed using a computing device and an imaging system that may include a camera and an illumination system (e.g., imaging devices 312 and 313 and illumination components 314 of FIG. 3) for imaging the surface of a patient's eye. The method determines the position and orientation of the eye by using the position of detectable features of the eye in the image (e.g., the pupil, limbus, iris features, etc.) and the position of the reflection of the illumination system at the cornea. The position of the eye is determined during a procedure or other time during which the patient is expected to be properly positioned and fixating with reference to an optical axis of the ophthalmic device. The operator may start the process by providing feedback (e.g., by pressing one or more buttons) and/or the operator may start the sequence which is then followed by the patient. Optionally, the operator may provide confirmation of the patient's compliance with the procedure.

The method 700 illustrates an embodiment for implementation by a computing device of an ophthalmic device that may include a retina OCT imaging device. To determine an absolute fixation position, the computing system determines whether fovea detection information is available (step 702). Fovea detection information may be available, for example, if the ophthalmic device includes a retina imaging device that scanned the patient's eye while the patient was properly fixating. If fovea detection information is available, the

method proceeds to step 704 where the computing system identifies eye tracking images that correspond to the detected fovea data (e.g., as described above with reference to FIG. 3). In step 706, the system calibrates the offset and gain and calculates absolute fixation parameters using the corresponding images. The patient's eye may then be tracked during a procedure using eye tracking images, the fixation parameters and calibrated equations.

Referring back to step 702, if fovea detection is not available then the method uses the captured images of the eye (e.g., images of the surface of the eye) to estimate the absolute fixation parameters. In step 720, the computing device receives a stream of captured images from the camera, calibrates the offset and gain values using at least one pair of images captured from different cameras disposed at known locations, and determines a position and orientation of the eye in each of a plurality of images. The computing device may process each received image or a subset of the received images (e.g., in accordance with processing constraints). The images may be received before/during a procedure and/or after a procedure when analyzing captured data.

After the position and orientation of the eye is determined for a series of captured images, a histogram is generated of the determined positions and orientations in step 730. In some embodiments, the position and orientation information include a pixel position of the center of the pupil in each of the images, which is used to construct a two-dimensional histogram of (x,y) coordinates. The position and orientation information may include an absolute position and orientation of the eye determined from each of the images, which is used to construct a two-dimensional histogram. Other representations of the position and orientation data may also be used (e.g., a heat map) in the present method. In some embodiments, operator feedback may be used to indicate images in which the patient has been instructed to fixate and/or to indicate whether the patient has not been fixating, and the corresponding images can be added to or discarded from the analysis. A procedure may be conducted in which the operator of the system instructs the patient to fixate on an object during a measurement sequence.

Referring to FIG. 8, a heat map 800 is illustrated showing an example distribution of fixation points the patient has looked at. The map may be color coded, three-dimensional, or otherwise include indicia to track the frequency in which the patient has fixated at certain spots. Other indicators (e.g., a color close to a background color) may be used to indicate a short time of fixation at that spot. In the illustrated embodiment, an area 810 of the heat map shows the most common coordinates and may indicate the position and orientation of the patient's eye while properly fixating on a target object. The dashed circle 820 indicates positions and orientations that are within a threshold offset to be chosen for a fixation determination depending on the level of precision needed for a procedure or analysis.

FIG. 9 illustrates an example histogram 900 plotting eye coordinates detected from captured images. The maximum of this distribution 910 may be used to estimate the position and orientation of the fixated eye (e.g., by identifying the position and orientation in which the patient was most often fixating). This estimated position and orientation may be used as a reference position for further eye fixation determinations. For example, an analysis of medical data taken in a measurement sequence, may use only the data points acquired when the eye had an orientation and position within an acceptable offset (e.g., as indicated by circle 920) from

the reference position (e.g., which is based at least in part on the maximum of the histogram).

As previously discussed, the histogram **900** may be constructed by plotting the fixation points determined from the captured images. For example, the histogram may track eye position as a series of pixel locations of the detected pupil or an otherwise identified center of the eye (e.g., as determined from reflections or other measurements). As the sequence of images is received and analyzed, a pattern may emerge indicating a position in which the patient is most often fixating. In some embodiments the values in the histogram may include an average of adjacent pixels and/or incorporate other smoothing.

Referring back to the method **700** of FIG. 7, in step **740** the histogram is analyzed to detect a fixation position. As previously discussed, the fixation position may relate to a maximum value of the histogram that meets certain analysis criteria. For example, a maximum may be selected based on a variety of factors including a degree of the maximum over the average value, a degree over a threshold value for a given number of images, etc. In some embodiments, the eye tracking continues during the procedure and the maximum/fixation position may be updated in real time as more images are analyzed.

Referring to step **750**, if no acceptable maximum is found (or other fixation point criteria met), then eye fixation information is not available through this process. In some embodiments, the eye tracking continues during the procedure and the maximum/fixation position may be identified and/or updated in real time as more images are analyzed.

In step **760**, the calibration offset and gain and estimated fixation parameters are determined (e.g., fixation position and offset radius acceptable for a procedure) based on the detected fixation information. The patient's eye may then be tracked during the procedure in step **708**, using the eye tracking images and the estimated fixation parameters.

Referring to FIG. 10, an example system **1000** for implementing the method of FIGS. 7-9 will now be discussed. A computing device **1002** (such as computing device **510** of FIG. 5) is communicably coupled to ophthalmic equipment **1060** and is configured to perform processes associated with an eye tracker **1030** and an ophthalmic procedure **1040**. The computing device **1002** may be configured to perform a retina image analysis (through retina image analysis module **1010**) using a retina imaging device (if available) of the ophthalmic equipment **1060** and store retina image data **1012**. The computing device **1002** further includes fixation analysis module **1020**, for performing an implementation of the method illustrated in FIG. 7 or other method for estimating absolute fixation parameters. In one embodiment, the fixation analysis module **1020** receives and analyzes streams of eye images captured by multiple cameras (e.g., imager A and imager B) of the eye tracker **1030**, constructs and analyzes a histogram of fixation positions, and determines reference positions and associated radii. The fixation data, including histogram data, may be saved in a storage **1022** (e.g., a memory or storage device).

In some embodiments, computing device **1002** includes a processor that is configured to perform program instructions stored in a memory, which may include the fixation analysis module **1020**, the optional retina image analysis module **1010**, the eye tracker **1030** and processes associated with the ophthalmic procedure **1040**.

The fixation analysis module **1020** may be configured to analyze the relative gaze of a patient's eye using images captured by the eye tracker **1030**. The fixation analysis module **1020** may calibrate the measurements using a pair of

images captured from different cameras to derive a calibration offset and gain, which allows for accurate determination of the eye position and orientation from image pixel coordinates of eye characteristics. The fixation analysis module **1020** may construct a histogram tracking gaze orientation (e.g., pitch and yaw of the eye, relative up/down and left/right offsets, curvature/rotation, etc.) and analyze peak values of the histogram (e.g., the number of data values at each location) to get an estimate of the absolute reference. In some embodiments, the fixation analysis module **1020** estimates an optical axis of the eye and an intersection with the eye tracker camera to track the gaze orientation.

The eye tracker **1030** may be configured to capture, store and process images of the patient's eye. The eye tracker **1030** may be configured to determine a patient's eye position and origination from one or more captured images for further analysis by the fixation analysis module **1020**. In some embodiments, each analyzed image may include an x,y position representative of an eye position and orientation (e.g., rotation around the x axis and y axis). The eye tracker may use information about relative orientation changes from one image to another in connection with an absolute fixation position (e.g., determined through retina image analysis **1010**) or estimated absolute fixation position (e.g., determined through fixation analysis module **1020**). In some embodiments, the fixation analysis module **1020** operates on an assumption that the patient was attempting to fixate most of the time, and that the estimated absolute fixation position can be determined by constructing a histogram of x and y rotation and determining the gaze orientation that is most prominent. In various embodiments, the histogram can be constructed of pixel coordinates, rotation around x and/or y, offset values, or other data. Each image can provide a coordinate pair representing calculated eye gaze orientation which is added to the histogram.

In some embodiments, the fixation analysis module **1020** is configured to analyze the histogram by detecting one distinct peak (e.g., prominent peak surrounded by smaller peaks) and determining a level of confidence that a fixation position has been detected. If no clear peak is detected, then a confidence level may be low. A radius around a detected peak may be used (e.g., humans can fixate plus/minus 0.5 degree). The threshold of peak to average and/or size of the radius may change depending on system and procedure requirements.

The computing device **1002** may include one or more neural networks trained to make one or more determinations disclosed herein, including analyzing histogram data to determine whether an eye fixation position can be determined. In some embodiments, the fixation analysis may further include a comparison of known eye tracking images and/or eye fixation parameters for the patient and/or other patients. For example, one or more images may be input into a neural network trained using historical data to determine whether the eye in an image is fixating.

In various embodiments, the operator may be provided with feedback on whether the patient is or is not fixating on this axis during the data acquisition, even when the retina imaging data is not available (e.g., not part of the system and/or fovea detection not available before procedure). The systems and methods disclosed herein provide a cost-efficient solution that is suitable for use with an ophthalmic diagnostic device that uses an image capture device and an illumination system as described herein.

As will be understood by those skilled in the art, the method of the illustrated embodiment provides improved techniques for independently verifying whether the patient's

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eye is properly fixating on the target object during operation. By detecting the fovea at a specific point in time, the system may determine where the line of sight/visual axis is located for the patient. This information allows the system to determine whether the patient is currently fixating during a measurement sequence or other diagnostic or corrective procedure. This method combines a system that images the retina and a system that tracks the eye using surface information. From the position of the fovea in the retina image, the system can determine the eye tracking location and determine whether the eye is moving to the left or right/up or down. The system can track the user gaze, calculate an offset, determine current eye position and orientation, make determinations regarding eye fixation, determine data validity, and provide other features in accordance with the present disclosure.

Methods according to the above-described embodiments may be implemented as executable instructions that are stored on non-transitory, tangible, machine-readable media. The executable instructions, when run by one or more processors (e.g., processor 512) may cause the one or more processors to perform one or more of the processes disclosed herein. Devices implementing methods according to these disclosures may comprise hardware, firmware, and/or software, and may take any of a variety of form factors. Typical examples of such form factors include laptops, smart phones, small form factor personal computers, personal digital assistants, and/or the like. Portions of the functionality described herein also may be embodied in peripherals and/or add-in cards. Such functionality may also be implemented on a circuit board among different chips or different processes executing in a single device, by way of further example.

Although illustrative embodiments have been shown and described, a wide range of modification, change and substitution is contemplated in the foregoing disclosure and in some instances, some features of the embodiments may be employed without a corresponding use of other features. One of ordinary skill in the art would recognize many variations, alternatives, and modifications. Thus, the scope of the invention should be limited only by the following claims, and it is appropriate that the claims be construed broadly and in a manner consistent with the scope of the embodiments disclosed herein.

What is claimed is:

1. A system comprising:

an eye tracker configured to capture a first image of an eye from a first location and a second image of the eye from a second location;

a diagnostic device configured to perform an eye diagnostic procedure while tracking a position and orientation of the eye using the eye tracker; and

a control processor configured to:

detect a first plurality of eye characteristics from the first image, the eye characteristics having first corresponding image coordinates;

detect a second plurality of eye characteristics from the second image, the eye characteristics having second corresponding image coordinates; and

determine a calibration offset and a calibration gain based at least in part on the first corresponding image coordinates, the second corresponding image coordinates, the first location and the second location,

wherein the diagnostic device is configured to modify the eye diagnostic procedure based, at least in part, on data representative of eye fixation parameters and a tracked eye position.

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2. The system of claim 1, wherein the control processor is further configured to:

determine an eye fixation position and orientation relative to an optical axis of the eye tracker based at least in part on the first corresponding image coordinates and/or the second corresponding image coordinates.

3. The system of claim 2, wherein the control processor is further configured to:

estimate eye fixation parameters based at least in part on the determined eye fixation position and orientation; receive a plurality of images from the eye tracker; and track a current eye position and orientation by analyzing at least one image from the first plurality of images to determine the current eye position and orientation relative to the eye fixation parameters;

wherein the eye fixation parameters comprise a reference position and orientation of the eye when fixated.

4. The system of claim 2, wherein the control processor is further configured to determine the fixation position relative to the optical axis of the eye tracker by constructing and analyzing a histogram of detected eye positions and orientations.

5. The system of claim 4, wherein analyzing the histogram further comprises determining whether coordinates of a relative maximum value comprise a fixation position and orientation; and

wherein determining whether coordinates of the relative maximum value comprise a fixation position and orientation further comprise comparing the relative maximum value with a threshold and/or an average coordinate value of the histogram.

6. The system of claim 1, further comprising:

a retina imaging system comprising an optical coherence tomography (OCT) scanner configured to perform a retinal scan.

7. The system of claim 6, wherein the eye tracker is further configured to capture a stream of images of the eye during the retinal scan;

wherein the retina imaging system is further configured to:

capture a plurality of retinal images of the eye;

detect whether a fovea is present in one or more of the plurality of retinal images of the eye; and

identify a first retinal image from the plurality of retinal images of the eye having the detected fovea; and

wherein the control processor is further configured to: determine a corresponding image from the stream of images having a temporal proximity to the first retinal image; and

analyze the corresponding image to determine eye fixation parameters.

8. The system of claim 1, wherein the control processor is configured to track the eye position and orientation and calculate an offset from the eye fixation parameters and

determine if the offset is less than a threshold value;

wherein when the offset is less than the threshold value the eye is determined to be fixated and the control processor generates an indication of fixation; and

wherein when the offset is greater than the threshold value the eye is determined to be out of alignment and the control processor generates an indication of no fixation.

9. The system of claim 1, wherein the control processor is further configured to perform an eye diagnostic procedure and track eye position using the eye tracker during the eye diagnostic procedure.

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10. A method comprising:
 capturing a first image of an eye from a first location;
 capturing a second image of the eye from a second
 location that is different than the first location;
 performing an eye diagnostic procedure while tracking 5
 the position and orientation of the eye;
 detecting a first plurality of eye characteristics from the
 first image, the eye characteristics having first corre-
 sponding image coordinates;
 detecting a second plurality of eye characteristics from the 10
 second image, the eye characteristics having second
 corresponding image coordinates;
 determining a calibration offset and a calibration gain
 based at least in part on the first corresponding image
 coordinates, the second corresponding image coordi-
 nates, the first location and the second location; and 15
 modifying the eye diagnostic procedure based, at least in
 part, on data representative of eye fixation parameters
 and a tracked eye position.
 11. The method of claim 10, further comprising:
 capturing a stream of images of the eye; 20
 detecting an eye position and orientation in the stream of
 images based at least in part on coordinates of the
 detected eye characteristics, the calibration offset and
 the calibration gain; and
 determining an eye fixation position and orientation rela- 25
 tive to an optical axis.
 12. The method of claim 11, further comprising:
 estimating eye fixation parameters based, at least in part,
 on the determined eye fixation position and orientation; 30
 and
 tracking the eye position and orientation by analyzing one
 or more images from the stream of images to determine
 the eye position and orientation relative to the eye
 fixation parameters.
 13. The method of claim 12, wherein the eye fixation 35
 parameters comprise a reference position and orientation of
 the eye when fixated.

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14. The method of claim 12, further comprising tracking
 an eye position and orientation and calculating an offset
 from the eye fixation parameters and determine if the offset
 is less than a threshold value;
 wherein when the offset is less than the threshold value
 the eye is determined to be fixated and the control
 processor generates an indication of fixation; and
 wherein when the offset is greater than the threshold value
 the eye is determined to be out of alignment and the
 control processor generates an indication of no fixation.
 15. The method of claim 11, further comprising training
 a neural network to receive the stream of images and output
 a determination of an eye position.
 16. The method of claim 11, further comprising detecting
 the fixation position relative to the optical axis by construct-
 ing and analyzing a histogram of detected eye positions and
 orientations;
 wherein analyzing the histogram further comprises deter-
 mining a relative maximum value.
 17. The method of claim 11, further comprising:
 performing a retina imaging scan of the eye using an
 optical coherence tomography (OCT) scanner.
 18. The method of claim 17, further comprising:
 capturing a plurality of retinal images of an eye from the
 retina imaging scan;
 capturing a stream of images using an imaging device
 configured to image a surface of the eye;
 detecting whether a fovea is present in one or more of the
 plurality of retinal images;
 identifying a first retinal image from the plurality of
 retinal images having the detected fovea;
 determining a corresponding image from the stream of
 images having a temporal proximity to the first retinal
 image; and
 analyzing the corresponding image to determine eye
 fixation parameters.

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